Porsche Engineering Services, Inc.

ULSAC Validation Program

Amendment Report
January 2001

to the

UltraLight Steel Auto Closures Consortium

PORSCHE
Engineering Services, Inc.

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ULSAC Amendment Report– January 2001

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1 ULSAC Background

Additional mass reduction by manufacturing the Panel Front Door Outer utilizing the sheet hydroforming process was investigated.

Background

In April 2000 the ULSAC Consortium and Porsche Engineering Services, Inc. (PES) released the results of the ULSAC Validation Phase featuring a stamped Panel Front Door Outer for the building of the Demonstration Hardware (DH) door structure. This door structure with the stamped Panel Front Door Outer utilized BH260 in a material thickness of 0.7mm and had a normalized mass of 13.27 kg/m^2. The selection of material for the stamped Panel Front Door Outer was based on comparative testing for dent resistance and oil canning using three material grades (BH210, BH260, DP600) in two material thicknesses (0.6 and 0.7mm).

Furthermore, additional mass reduction by manufacturing the Panel Front Door Outer at a lower gauge, utilizing the sheet hydroforming process was also investigated in the Validation Phase. This process was intended to gain additional stretch in the middle area of the panel, with the aim of enhancing dent resistance and oil canning performance. The development work for sheet hydroformed tooling and forming simulations to establish process parameters began in parallel with the development of the stamping tool in early 1999. As discussed in the *ULSAC Engineering Report April 2000, Chapter 12 – Summary and Results*, the sheet hydroforming process was and is still under development

1.1 Scope of Work

Porsche Engineering Services, Inc. in Troy, Michigan, executed this program. The DH build was again done at the Porsche AG R&D Center in Weissach, Germany. PES program responsibilities included the following program tasks for ULSAC DH door structure build utilizing sheet hydroformed Panel Front Door Outers:

- Program Management and Planning
- Build Management for the Construction of the Demonstration Hardware
- Build of Demonstration Hardware
- Part Supplier/Manufacturer Evaluation and Selection
- Physical Testing
- Documentation of the Manufacturing Process
- Documentation of Dent Testing Results
- Economic Analysis
- Amendment to Engineering Report April 2000

1.2 Materials

The same materials as utilized for the manufacturing of the stamped panel door outers were used for the manufacturing of the test doors with sheet hydroformed door outer panels. The material for the sheet hydroformed Panel Front Door Outer manufacturing to be used in the DH door structures was determined after comparative testing for dent resistance and oil canning and comparison with test results from the ULSAC test doors with stamped Panel Front Door Outers.

1.3 Comparative Testing for Dent Resistance and Oil Canning

The same three Consortium member laboratories, as mentioned in the *ULSAC Engineering Report – April 2000*, again conducted comparative testing for dent resistance and oil canning. The results of these tests were used to select the most suitable steel and thickness for demonstration hardware build with sheet hydroformed Panel Front Door Outers. Eighteen doors with sheet hydroformed door outer panels in two material thicknesses utilizing three different steel material grades were manufactured, tested, and documented. Members of the ULSAC Consortium, together with PES, selected the material thickness and grade used for the DH build.

2 Materials & Processes

Three materials BH210, BH260 and DP600 in two thicknesses - 0.6mm and 0.7mm were used to compare testing results

Background

During the last several years the steel industry has developed a range of new high strength steel products. In the ULSAC program, high strength steels are defined as steels with yield strengths of 210 MPa – 550 MPa on the finished part. A number of modern steel grades were considered for the Panel Front Door Outer with the goal to achieve mass reduction, while maintaining satisfactory dent resistance and oil canning performance. These steels included micro-alloyed, bake-hardenable, interstitial-free, isotropic and dual phase steel.

In order to compare the performance of the stamped Panel Front Door Outer with the performance of the sheet hydroformed Panel Front Door Outer, the following three materials BH210, BH260 and DP600 in two thicknesses – 0.6 mm and 0.7 mm - were used. The grade numbers (210, 260) for bake-hardenable (BH) steels refer to the yield strength, while the grade number (600) for the dual phase (DP) steel refers to the ultimate tensile strength.

Material	Material Thickness
BH210	0.6mm
	0.7mm
BH260	0.6mm
	0.7mm
DP600	0.6mm
	0.7mm

Figure 2-1 Materials used for test doors for dent resistence and oil canning

2.1 Sheet Hydroforming Process Description

2.1.1 Active Hydromechanical Sheet Metal Forming General Process Description

Hoods, roofs and door outer panels (large body panels) produced by conventional forming methods often lack sufficient dent resistance in the center area of the part. The low degree of stretch in the center results in an insufficient work hardening effect. Therefore, material thickness has to be increased to improve performance. Increasing material thickness adds mass. To overcome this effect, the active hydromechanical sheet hydroforming process (AHM) offers a possible alternative manufacturing process.

The AHM process is a multi-stage forming technology with a liquid working medium. The die consists of three main components: a drawing ring, which is designed as a working medium chamber, the blankholder (binder) and the drawing punch. In the first stage, the die is open and the flat steel sheet is loaded onto the drawing ring (see Figure 2.1.1-1).

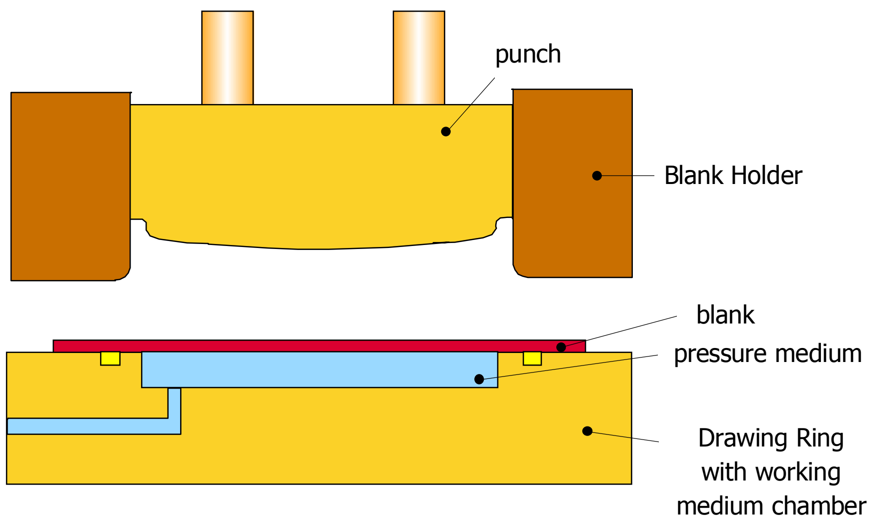


Figure 2.1.1-1 First stage of the AHM process- Loading of the steel blank

In the second stage, the die is closed and the blankholder clamps the blank. A pressure intensifier generates preforming pressure in the drawing ring -working medium chamber. In this first preforming step, a working medium pressure of approximately 6 bar is applied to achieve prestretch in the middle of the part. A blankholder force of approximately 2000 tons is necessary to avoid blank movement. Depending on the punch displacement and the working medium pressure, the plastic strain in the middle of the part can be adjusted.

In the ULSAC program the preforming was done with a punch displacement of 115mm above the blank. This preforming process causes the first marks of the die on the inside of the prestretched blank in the area A and B (feature lines of the ULSAC Panel Front Door Outer) (see Figure 2.1.1-3).

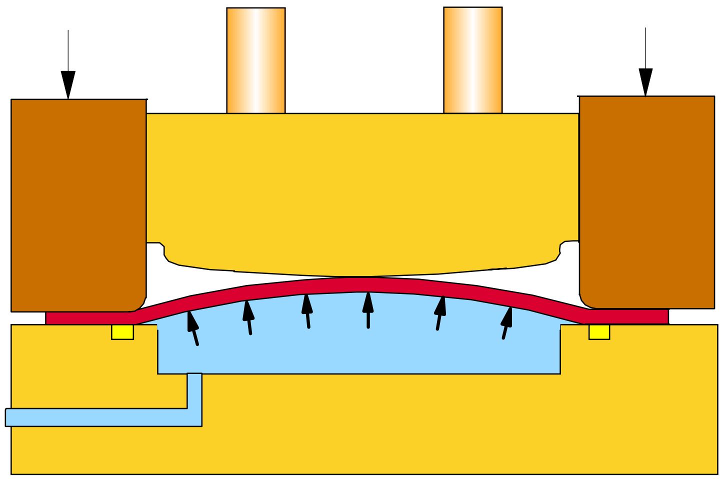


Figure 2.1.1-2 Preforming Process of AHM

The third step is the reverse drawing where the punch is lowered and the preformed material is pushed in the opposite direction into the working medium chamber (see Figure 2.1.1-4). With this reverse motion, the first contours of the ULSAC Panel Front Door Outer are formed. During this step the working medium pressure is decreased in a controlled manner.

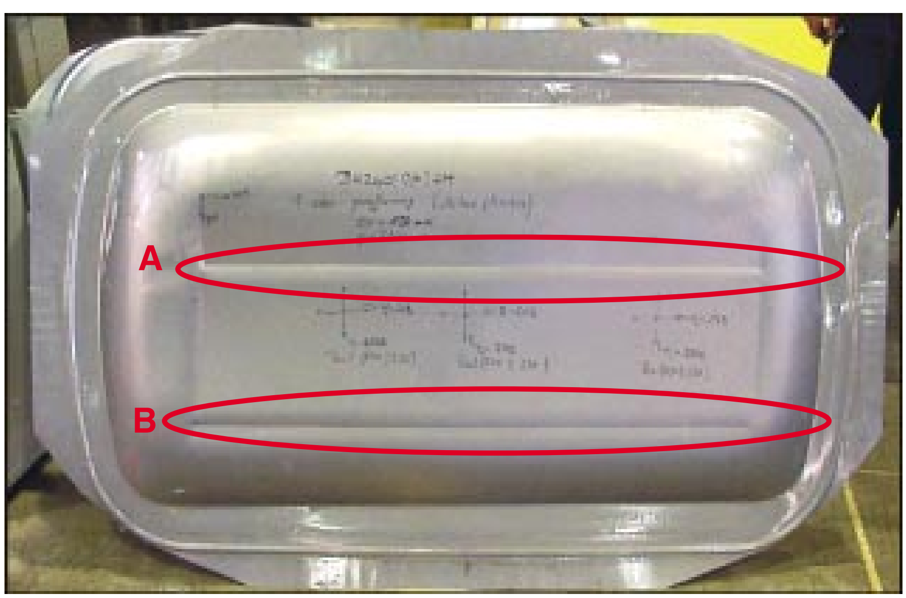


Figure 2.1.1-3 First contours after preforming

In the final step the maximum working medium pressure is applied and closely forms the part to its final shape (calibration). The maximum working medium pressure is dependent on the yield strength of the material, material thickness and the minimum concave radius of the part as specified in the design.

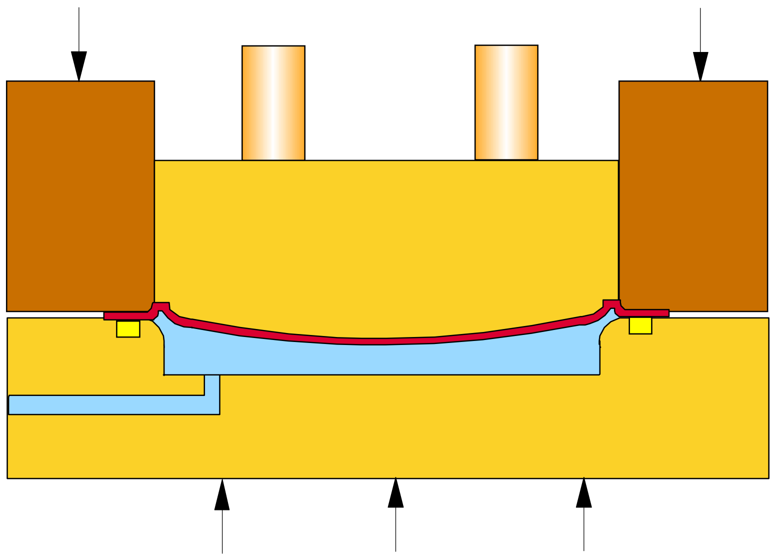


Figure 2.1.1-4 Final step in the AHM Process is calibration

3 Forming Simulation

Incremental forming simulation was used to simulate the AHM process for all three material types in both thicknesses.

Background

Currently, two types of forming simulation are used to assess parts manufacturing feasibility.

One-step forming simulation provides designers with an indication of manufacturing feasibility. Here, the analysis does not simulate the complete forming process because it is performed without any tooling boundary condition input. One-step simulation uses only material data and the geometry of a designed part to calculate material strains by mapping back to the flat sheet. Feasibility is determined by comparison with the forming limit of the material.

Incremental forming simulations model the entire forming process. Here, the analysis inputs include the part and the tool geometry, the material properties of the part, the blank size and shape, frictional coefficient, press conditions and the draw-bead effects. The outputs show levels and distribution of material strain, failure prediction, thickness profiles and wrinkling tendency.

To predict the feasibility of the Panel Front Door Outer manufacturing using the AHM process, all three materials in both thicknesses were simulated using the incremental forming simulation.

3.1 Development trends in incremental forming simulation

The state-of-the-art in incremental FE-simulation of sheet metal forming incorporates a combined implicit and explicit integration of time. In general, tooling is described as rigid. Material can be described using shell elements, membrane elements or volume elements. With this type of simulation, it is possible to generate first process parameters, which offers the possibility to predict problems prior to parts manufacturing.

Development trends in forming simulation consider new concepts such as elastic die components, segmented blankholder, and spring-back behavior of formed parts.

3.2 Applied FE Program

The simulation of the hydromechanical sheet metal forming process was performed using the incremental forming simulation program Autoform™.

AutoForm™ is an implicit FE-program. The displacement of the nodes is calculated by a static balance. AutoForm™ uses membrane elements that are physically extended so that a special kind of bending effect can be calculated. By using a membrane element formulation and automatic mesh refinement during the iterations, short calculation times can be realized with high accuracy. However, the accuracy is not as high as a simulation calculated with shell elements. The sheet hydroforming process was simulated in a new beta version application.

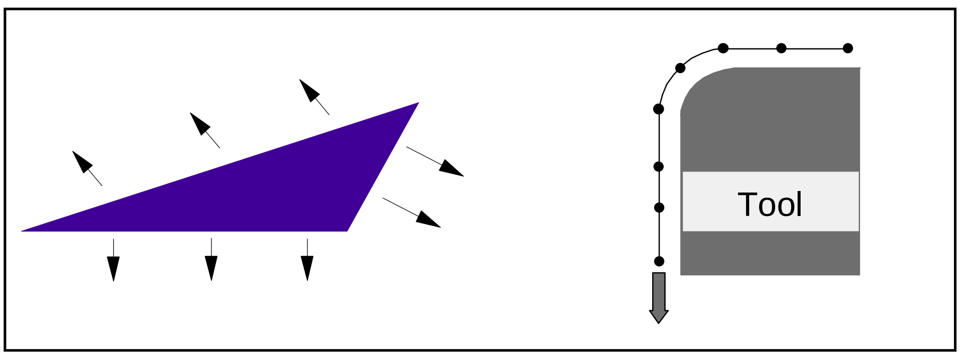


Figure 3.2-1 Depiction of membrane elements

3.2.1 Forming Simulation of Active Hydromechanical Sheet Hydroforming

The requirements for the simulation of the hydromechanical sheet hydroforming (AHM) process are an effective contact algorithm, shell or membrane elements for the description of the blank, as well as the material input data of the flat sheet. The tool was described with rigid body elements, therefore it was not necessary to use material data for the tool. With the selected friction coefficient and the tool stiffness as input parameters, the tool was considered as a steel tool in the simulation.

The working medium pressure is simulated using a special pressure load model. The surface areas of the flat steel sheet, over which the pressure load should be applied, can be described by using pressure load elements. The preforming with working medium pressure could then be simulated by defining the pressure load distribution on those elements or by defining an increase of volume.

All three materials BH210, BH260 and DP600 in both thicknesses 0.7mm and 0.6mm were simulated prior to the manufacturing process. The material DP600 with the material thickness of 0.6mm was assumed to be the most difficult to form and is shown in the following figures. The calculations have been done with the Hill-model, which describes material behavior.

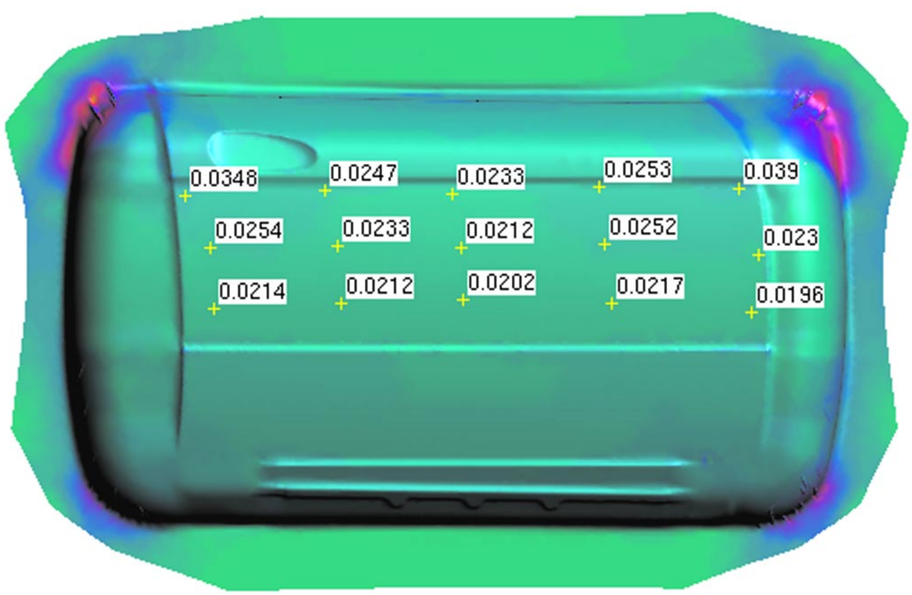


Figure 3.2.1-1 Major strain of Panel Front Door Outer (DP600 0.6mm)

Figure 3.2.1-1 shows the major strain distribution of the Panel Front Door Outer and indicates a major strain φ_1 of 2.1% in the middle area of the Panel Front Door Outer. The minor strain φ_2 of the active sheet hydroformed Panel Front Door Outer is shown in Figure 3.2.1-2. The corresponding minor strain number in the middle area of the part was calculated to be 1.1%.

Figure 3.2.1-2 Minor Strain of the Panel Front Door Outer (DP600 0.6mm)

The calculated plastic strain φ_v for the material DP600 with the material thickness 0.6mm is shown in Figure 3.2.1-3.

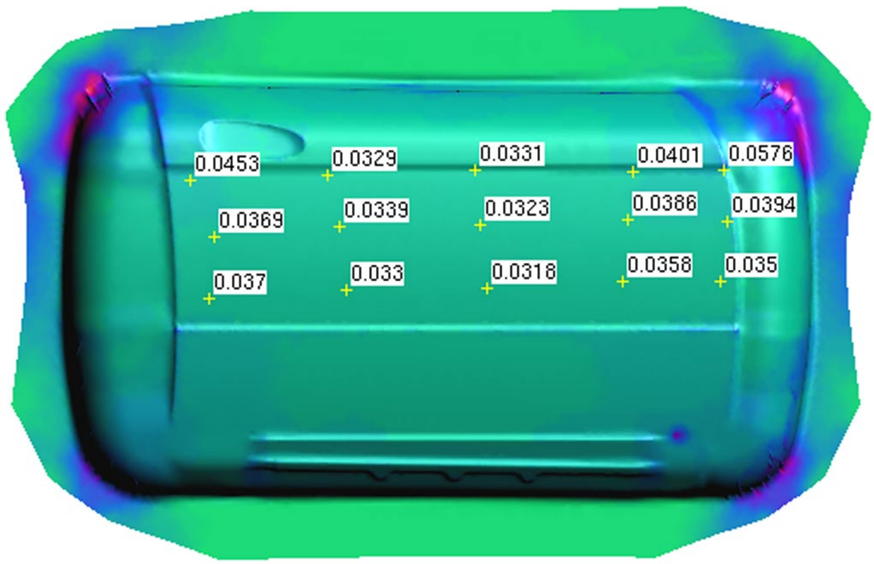


Figure 3.2.1-3 Plastic Strain of the Panel Front Door Outer (DP600 0.6mm)

Figure 3.2.1-3 indicates a plastic strain φ_v of 3.2% in the middle area of the Panel Front Door Outer. To make a statement about the manufacturing feasibility of the part an analysis of the thinning results is shown in Figure 3.2.1-4.

Figure 3.2.1-4 Thinning of the Panel Front Door Outer (DP600 0.6mm)

With an initial thickness of the flat steel sheet of 0.6mm the thinning in the middle area of the Panel Front Door Outer calculates to be 0.019mm, which is a result of the preforming process. The thinning results of the incremental forming simulation shows that the part is feasible to manufacture with the material DP600 with the sheet thickness of 0.6mm.

This incremental forming simulation of the ULSAC Panel Front Door Outer with the materials BH210, BH260 in both thicknesses 0.6mm and 0.7mm as well as the material DP600 with the material thickness 0.7mm indicates that parts are feasible to manufacture using all these materials.

A forming limit curve (FLC) for the material grade DP600 with the material thickness 0.6mm was used to verify the feasibility of the Panel Front Door Outer. The result of the forming simulation is shown in the forming limit diagram (FLD), Figure 3.2.1-5. The simulation predicted that the part can be manufactured without failure.

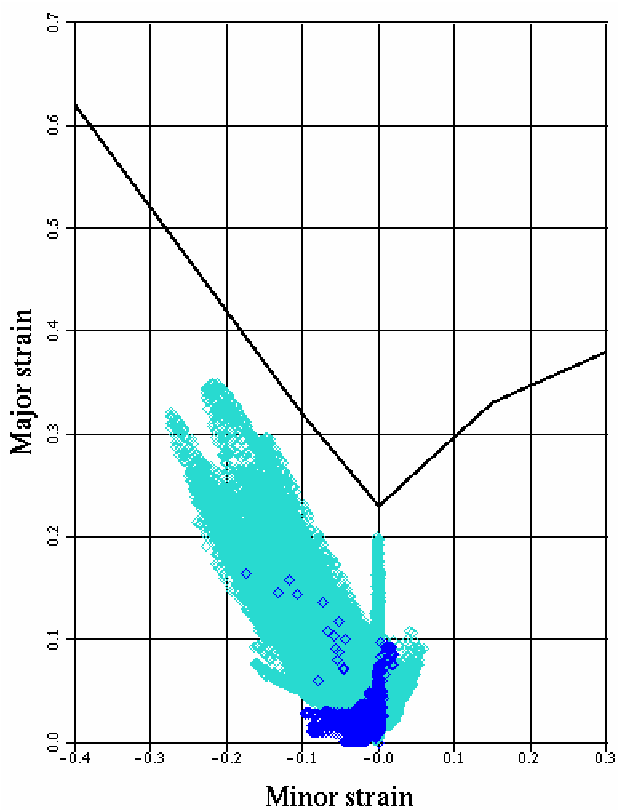


Figure 3.2.1-5 Forming Limit diagram of Panel Front Door Outer (DP600 0.6mm)

3.3 Conclusions

The incremental forming simulation utilizing the Autoform™ program to simulate the active hydromechanical sheet hydroforming process was helpful to predict plastic strain, material thinning and material failure in areas that were considerably influenced by the reverse drawing step. In general, the forming simulation indicated that the door outer part is manufacturable with each of the steel grades and thicknesses. The prediction of plastic strains in the middle area of the ULSAC Panel Front Door Outer caused by the working medium pressure is not accurate. The comparison of the calculated plastic strains and the measured plastic strains with circle grid analysis is documented in *Chapter 4 – Parts Manufacturing*.

4 Parts Manufacturing

With the combined hydromechanical manufacturing process, the required press force was reduced to 3,000 - 5,000 tons.

Background

Prior to parts manufacturing suppliers were selected. The main criteria for supplier selection was to consider suppliers experience in "production intent."

Other criteria for supplier selection were:

- Major OEM quality rating or ISO-9001 certification
- Available capacity for program
- Manufacturing process corresponds to the program timing
- Experience in production representative prototyping
- Prepared to enter simultaneous engineering prior to contract
- CAD/CAM systems compatibility with CATIA
- Cost competitiveness

4.1 Part Supplier Selection

Based on the criteria for supplier selection and PES' experience with tool & parts manufacturers in the UltraLight Steel Auto Body structure program, Schuler SMG GmbH & Co. KG was selected as the supplier for the Panel Front Door Outer manufacturing utilizing the sheet hydroforming process.

Schuler SMG GmbH & Co. KG was also chosen for its state-of-the art equipment and sheet hydroforming technology and because their facilities in Wilnsdorf and Waghaeusel are located near to Porsche's R&D Center, where the door structure was assembled. Company information is given in Table 4.1-1.

Company Name	Address	Number of Employees
Schuler SMG GmbH & Co. KG	Louis-Schuler Strasse 1, D-68753 Waghaeusel	560

Major Products
Hydraulic forming presses for the automotive industry • Conventional deep drawing • Sheet hydroforming • Tube hydroforming Blanking presses

Other Divisions	Customers	Major Equipment
Development of forming technologies Serial production of small lot sizes Prototyping	DaimlerChysler AG BMW AG Jaguar MAN AG Laepple GmbH & Co. KG	N/A

Table 4.1-1 Supplier Profile

4.2 Press Environment

The active hydromechanical sheet hydroforming process environment consists of a forming press, process control, a pressure intensifier, a forming tool, as well as a Polyurethane (PU)Calibration tool.

4.2.1 Forming Press

The hydraulic forming press is located at the Schuler-Hydroforming-Center in Wilsndorf Germany. The double action straight side press design with Hydro-mechanic pressure intensifier and quick tool change table is based on the air cushion principal. This press has a maximum press force of 10,000 tons. The maximum blankholder force, applied by six cylinders, is 2,000 tons. The maximum intensifier pressure is 4,000 bar.

Figure 4.2.1-1 Schuler SMG 10,000 ton press

4.2.2 Process Control

AHM process control defines the target values regarding blankholder forces for each cylinder and the function of the working medium pressure which is dependent on the punch displacement and time, as well as closing forces during calibration. This process control also verifies the actual values and diagnoses the machine conditions. Actual process data is displayed during the forming process.

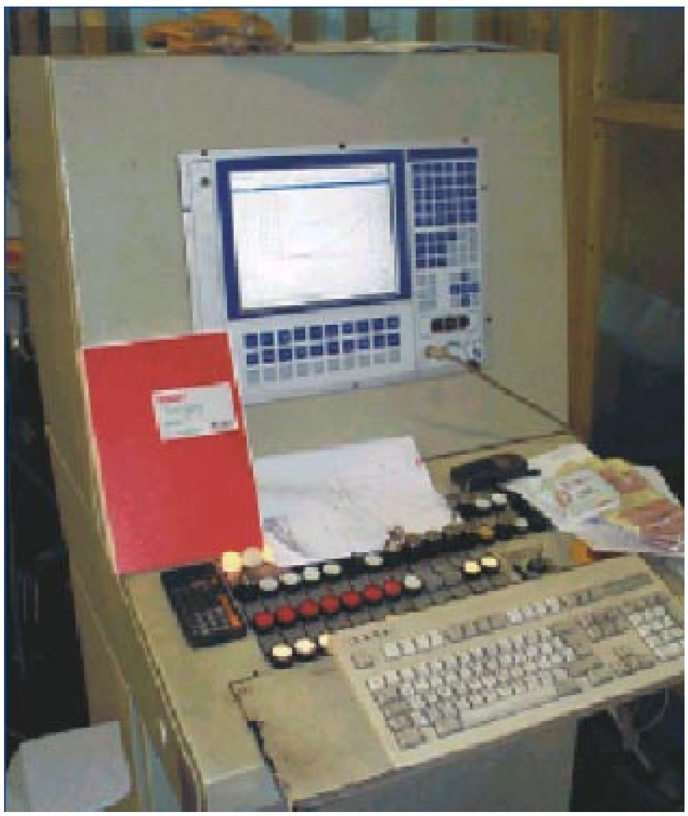


Figure 4.2.2-1 Process control unit

4.2.3 Pressure Intensifier

The pressure intensifier generates the pressure level in the working medium. The maximum pressure of the intensifier is 4,000 bar. In the ULSAC Program, the ports and hoses, as well as the working medium chamber were designed to resist a working medium pressure up to 300 bar (including measurement of the pressure and displacement system).

Figure 4.2.3-1 Pressure intensifier

4.2.4 AHM Forming Tool

The forming tool is designed in three parts; a lower die, blankholder and drawing punch. The lower die is a cast iron part, designed as a working medium chamber with a drawing ring. The blankholder is also a cast iron part. A circular splash ring mounted to the blankholder keeps fluid from leaking and serves as a guide for the drawing punch. The drawing punch is located inside the blankholder.

Figure 4.2.4-1 AHM door panel forming tool

4.3 Tooling Development for AHM process

Forming simulation (described in Chapter 3) predicted working medium pressures needed to form the panel, in press tryouts it was determined that higher pressures that those predicted were actually required. After several tryouts, the press environment was modified to reach a higher working medium pressure in the range of 300 bar. The working medium chamber was redesigned and updated to resist the increased pressure. In addition, the press was modified with new ports and hoses to resist the higher working medium pressure.

4.3.1 PU(Polyurethane)-insert description

A polyurethane (PU) insert solution was developed as an alternative to the use of a much larger press size.

The combination of high strength steel materials and small radii as specified in the parts design requires a high working medium pressure to form the part to its final shape.

The required working medium pressure p_w is dependent on the yield strength of the material (YS), the material thickness (t) and the minimum concave radius (r_{min}) of the part.

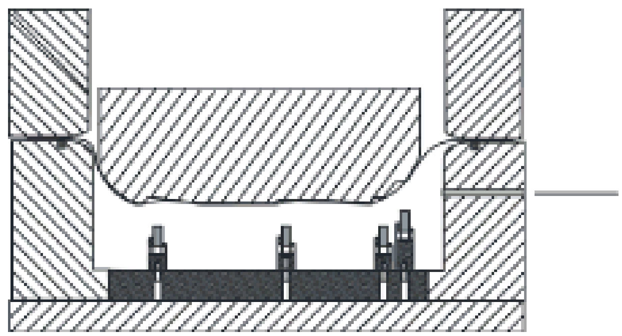
$$p_w = \frac{YS \bullet t}{r_{\min}}$$

The press closing force is computed as the product of the working medium pressure p_w and the projected surface area A_{proj} of the Panel Front Door Outer.

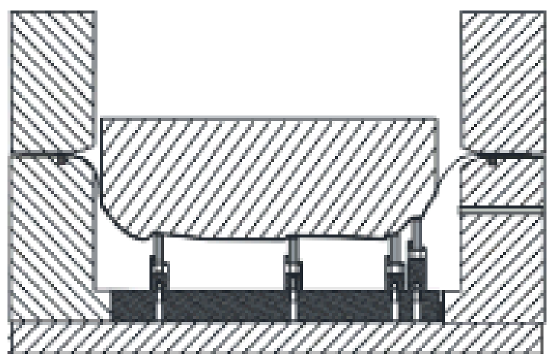
$$F = p_w \bullet A_{proj.}$$

With the material type DP 600 in a thickness of 0.6mm and a minimum radius of 3mm, the required working medium pressure is calculated to be approximately 700 bar. The projected surface of the sealed area of the blank inside the tool is $1.51m^2$. To calculate the press force, the working medium pressure must be multiplied by the projected surface, and results in a required press force of greater than 10,000 tons for the material DP 600 with a thickness of 0.6mm. This press size is not considered to be economical for Panel Front Door Outer manufacturing.

However, combining the hydromechanical manufacturing process with a calibration/ stamping process using PU-drawing cushions, the manufacturing process no longer requires the high calibration pressure to form the small radii in this part.



Step 1: Hydromechanical Forming



Step 2: Calibration nwith PU-drawing cushions

Figure 4.3.1-1 Combined hydromechanical manufacturing process

With this combined forming process, the required press force was reduced to 3,000 - 5,000 tons. This process allows the utilization of a smaller press. To validate this combined forming process prior to the tooling development, first tryouts were made using a small tryout tool (with a PU-cushion) on a segment of the ULSAC Panel Front Door Outer where a concave radius of 3mm had to be formed.

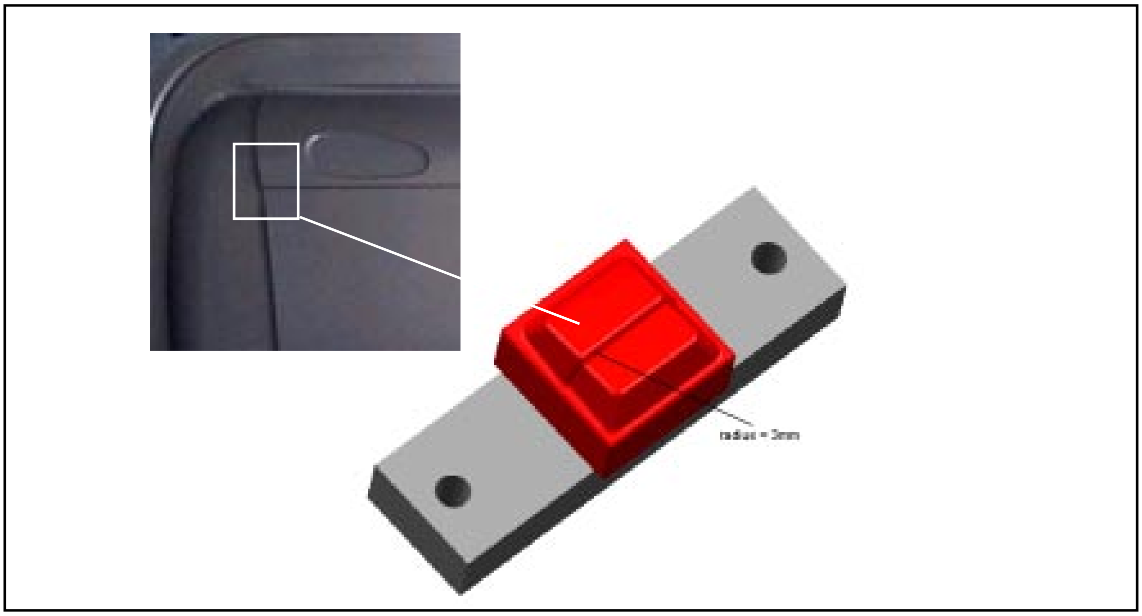


Figure 4.3.1-2 Segment of ULSAC Panel Front Door Outer with small tryout tool insert

The CAD-model of the tool arrangement and the manufactured small tryout tool for testing purposes are shown in Figure 4.3.1-3.

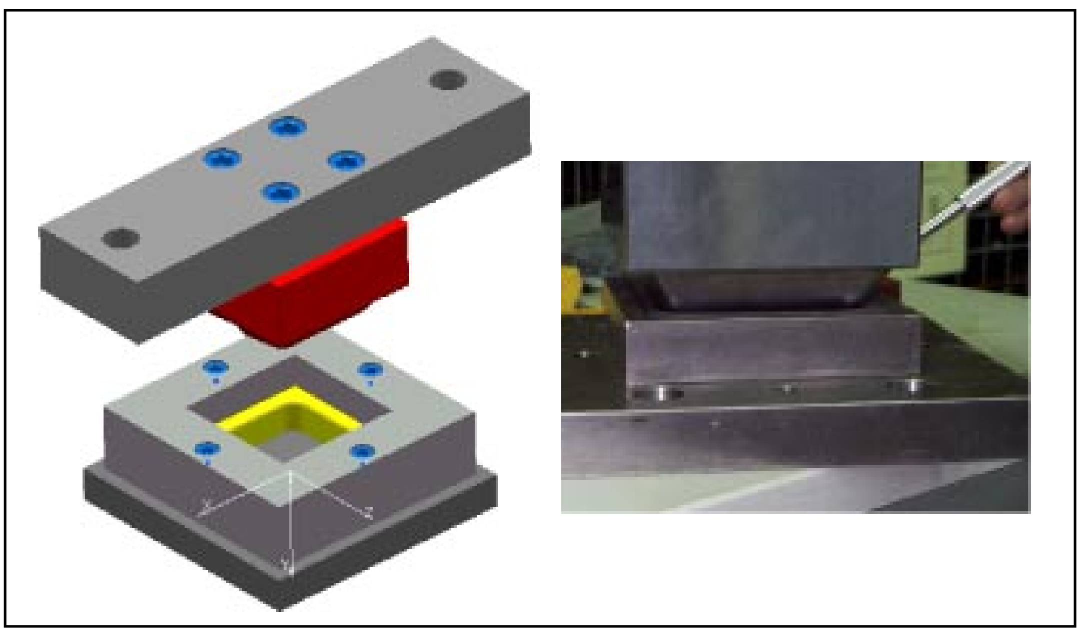


Figure 4.3.1-3 Small tool tryout CAD data and actual photo

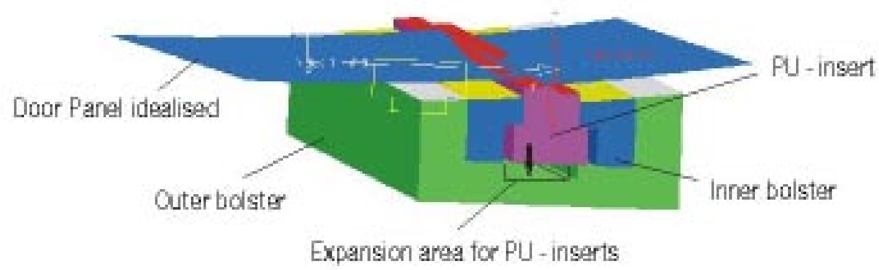


Figure 4.3.1-4 Pu calibration tool set-up

The experimental set-up of the small PU-calibration tool is described in Figure 4.3.1-4. There is an inner and outer bolster in which the PU-inserts are situated. The expansion area permits the PU-material to expand under pressure.

With the “Marc” simulation program, the contact normal stresses on the tool were calculated to determine the maximum pressure that could be applied on the PU-material without failure of this material.

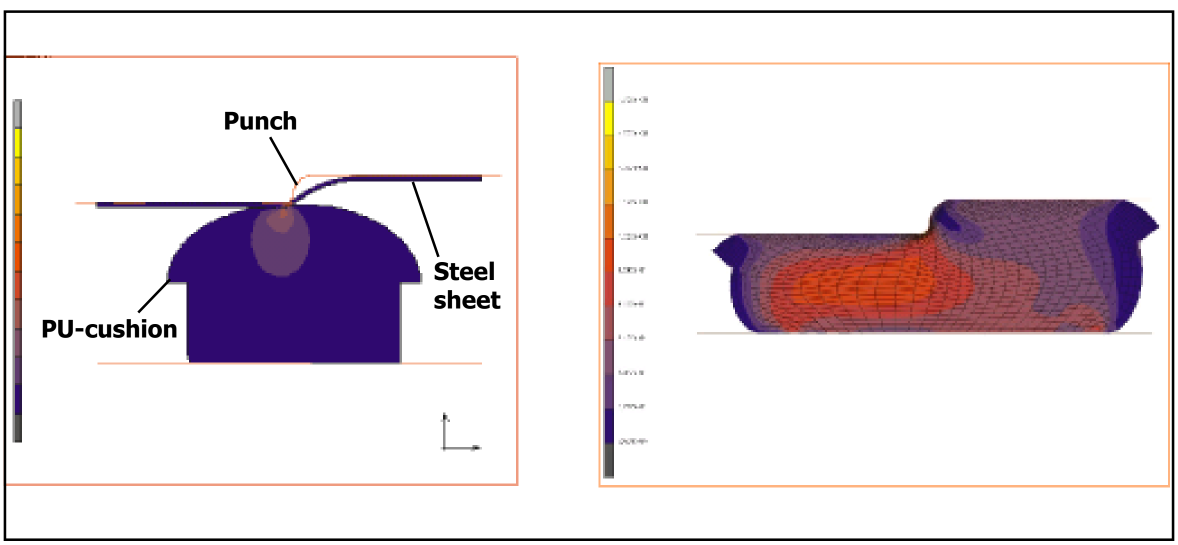


Figure 4.3.1-5 “Marc” simulation of PU-drawing cushions

The “Marc” simulation predicts that a pressure of approximately 1,000 to 1,500 bar could be applied using the PU-material. In this range of pressure, no failure of the PU-material will occur.

Figure 4.3.1-5 shows the CAD data of a cross section of the tool arrangement for the combined sheet hydroforming/PU-stamping process of the ULSAC Panel Front Door Outer in the deep drawing step. The final step (calibration) with local PU drawing cushions is shown in Figure 4.3.1-6. Figure 4.3.1-7 shows PU-calibration tool with the PU-cushion inserts.

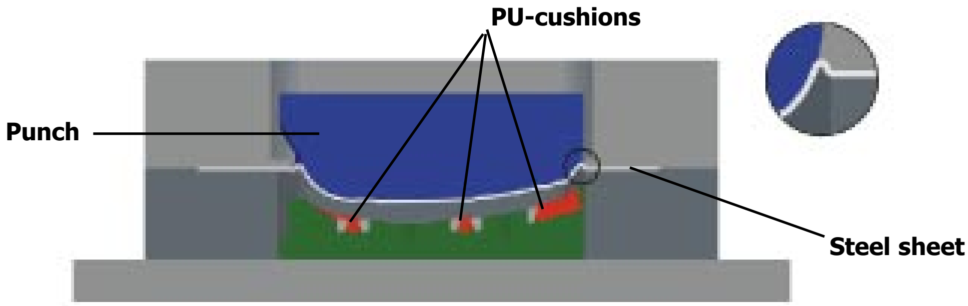


Figure 4.3.1-5 Cross section of PU calibration tool - Deep drawing step

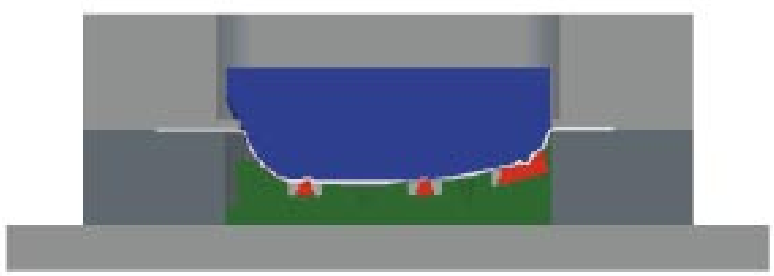


Figure 4.3.1-6 Cross section of PU calibration tool - Final calibration step

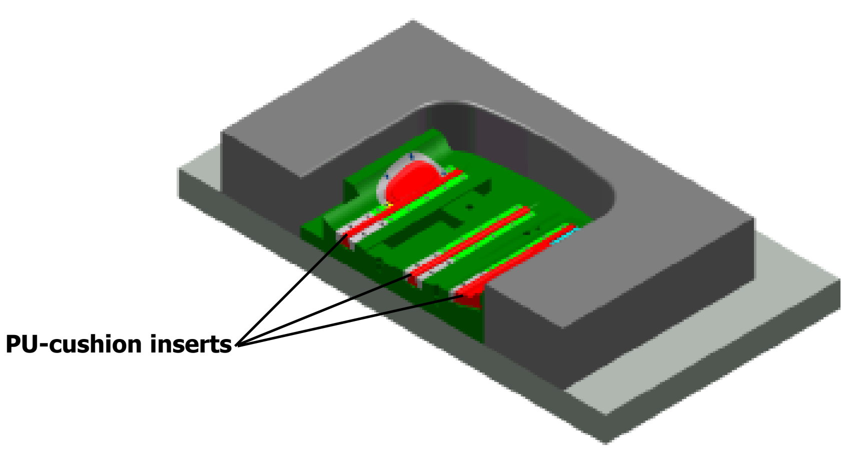


Figure 4.3.1-7 PU calibration tool with PU-cushion inserts

4.4 Circle Grid Strain Analysis

Circle grid strain analysis in the ULSAC program was performed to determine real strains or material thinning and material thickening of the three-dimensional formed parts. In the active hydromechanical sheet hydroforming process, the circle grid strain analysis was different to the analysis of the stamped parts in the ULSAC Program (Panel Front Door Inner Front/Rear, Panel Mirror Flag). The magnitude of deformation in the stamping process of these parts can be measured using circle grid patterns with small circles. The most interesting area in the active sheet hydromechanical sheet hydroforming process is the middle area of the Panel Front Door Outer, where the expected plastic strains are less than 8%. Those small plastic strains could not be measured by using a circle grid pattern with small circles.

The circle grid strain analysis in the active hydromechanical sheet hydroforming process was performed by applying circles on the flat steel sheet with an initial diameter of 100mm prior to the forming process. As a result of the preforming and the final forming, the initial diameter of the circles changed. These changes were measured into major strain ε_1 and minor strain ε_2. The logarithmic magnitude of deformation in major axis is calculated to be φ_1. The logarithmic magnitude of deformation in minor axis is calculated to be φ_2. With φ_1 and φ_2, the equivalent plastic strain φ_v is calculated by using the von-Mises formula:

$$\varphi_v = \frac{2}{\sqrt{3}}\sqrt{\varphi_1^{\ 2} + \varphi_2^{\ 2} + \varphi_1 \cdot \varphi_2}$$

Material	Thickness (mm)	Parts Manufacturing					
		Major Strain φ_1(%)	Minor Strain φ_2(%)	Major Strain φ_1(%)	Minor Strain φ_2(%)	Major Strain φ_1(%)	Minor Strain φ_2(%)
BH210	0.6	2.7	1.8	2.9	1.4	2.95	1.8
	0.7	2.9	2.0	3.0	2.3	3.1	2
BH260	0.6	3.75	2.0	3.75	2.0	3.75	2.4
	0.7	n/a	n/a	2.0	1.9	n/a	n/a
DP600	0.6	5.9	2.6	4.9	1.9	4.3	2.7
	0.7	3.0	2.0	2.7	2.0	2.6	2.2

Table 4.4-1 Major/Minor Strain Values, values from parts manufacturing

4.4.1 Comparison Forming Simulation with Parts Manufacturing

The comparison of the parts manufacturing and the forming simulation for the ULSAC Panel Front Door Outer was performed for the materials BH 210, BH 260 and DP 600 at thicknesses of 0.6mm and 0.7mm. The circles were applied on three different areas of the Panel Front Door Outer (see Figure 4.4.1-1).

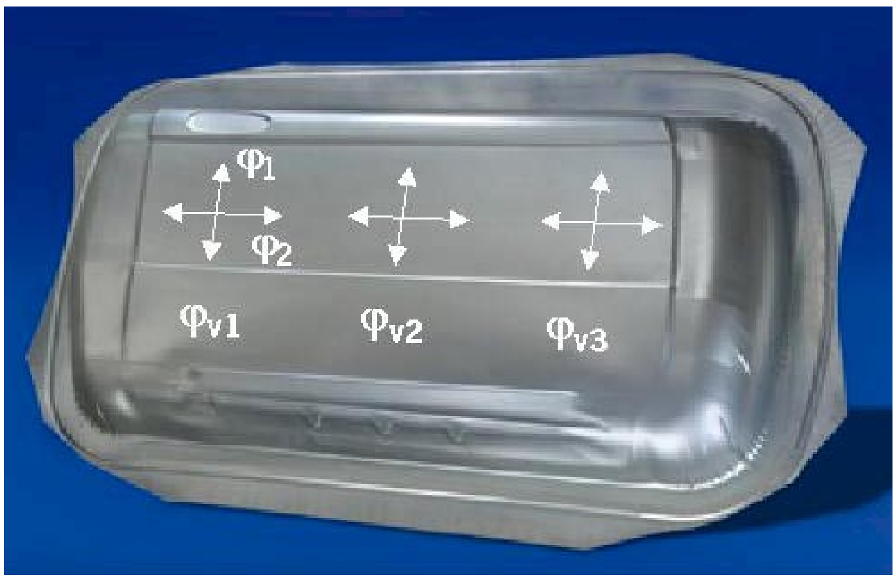


Figure 4.4.1-1 Circle Grid Placement

The plastic strain values calculated in the forming simulation by Schuler SMG, as well as the measured plastic strain values (parts manufacturing) of the three materials in both thicknesses are documented in Table 4.4.1-1.

Material	Thickness (mm)	Forming Simulation			Parts Manufacturing		
		φ_{v1}(%)	φ_{v2}(%)	φ_{v3}(%)	φ_{v1}(%)	φ_{v2}(%)	φ_{v3}(%)
BH210	0.6	4.3	3.2	4.7	4.5	4.3	4.7
	0.7	4.7	3.5	5.0	4.9	5.3	5.2
BH260	0.6	6.6	3.6	6.5	5.8	5.8	6.2
	0.7	4.9	4	5.0	n/a	3.9	n/a
DP600	0.6	3.4	3.2	3.9	8.7	7.0	7.1
	0.7	4.2	2.2	4.5	5.0	4.8	4.8

Table 4.4.1-1 Plastic Strain values between Forming Simulation and Parts Manufacturing (measured)

The press parameters for the tryouts were determined by calculating the hydromechanical sheet hydroforming process in the incremental forming simulation prior to manufacturing. The calculated plastic strain values φ_{v1} and φ_{v3} of the materials BH 210 and BH 260 are very close to the plastic strain values φ_{v1} and φ_{v3} measured by circles on the sheet hydroformed Panel Front Door Outer. The plastic strain values φ_{v2} calculated in the middle area of the Panel Front Door Outer are different in comparison to the measured plastic strain values φ_{v2}. The magnitude of deformation φ_{v1} and φ_{v3} is closely related to the reverse drawing step that is a kind of "deep drawing." Deep drawing processes can be calculated very accurately using the AutoForm™ software.

The magnitude of deformation φ_{v2} in the middle area of the sheet hydroformed Panel Front Door Outer is directly related to the preforming caused by the working medium pressure. The discrepancies in the calculated values and the measured values in this area could be a result of the insufficient pressure load modeled in the incremental AutoForm™ simulation.

The comparison of the plastic strains calculated in the forming simulation with those measured in the parts manufacturing process of the material DP 600 differ in dependence on the material thickness of this material. Compared to the parts manufacturing, the forming simulation of the Panel Front Door Outer with the material thickness 0.7mm calculates a smaller plastic strain $\varphi_{v2.}$ The plastic strains φ_{v1} and φ_{v3} of the incremental forming simulation are close to the values measured in the tryouts. Therefore, the results for the DP 600 material with the material thickness 0.7mm are comparable to the results of the materials BH 210 and BH 260.

Compared to the materials BH 210 and BH 260, as well as the material DP 600 wirh a thickness of 0.7mm, the circle grid strain analysis of the material DP 600 with the material thickness of 0.6mm indicates much higher plastic strain values. The measured plastic strains φ_{v1}, φ_{v2}, and φ_{v3} measured by circles on the sheet hydroformed Panel Front Door Outer are also much higher than the plastic strains calculated by forming simulation.

The comparison of the incremental forming simulation with the parts manufacturing was performed by a circle grid strain analysis. The incremental forming simulation of the active hydromechanical sheet hydroforming process with Autoform™ software is not accurate enough to predict plastic strains in the middle area of the ULSAC Panel Front Door Outer caused by the working medium pressure.

5 Testing & Results

The ULSAC DH door structure utilizing the sheet hydroformed Panel Front Door Outer was tested for structural performance, dent resistance and oil canning.

Background

The following explanations are strictly related to the chapters 10.2 – 10.8 of the *ULSAC Engineering Report, April 2000*. Detailed descriptions of the test equipment at the different test locations, the test set-up and procedure were given there. Targets for quasi-static and dynamic dent resistance were described there as well as requirements for oil canning. Once again, dent testing and oil canning was performed by a member steel laboratory in accordance with procedures (see Appendix for test results) established by the North America's Auto/Steel Partnership (A/SP), as set forth in A/SP's report entitled, "Procedures for Evaluating Dent Resistance of Steel Automotive Panels, Version 1.0 – June 1999."

As done in the previous report, 18 doors were tested. In this report, results are given for the ULSAC DH door structure with a sheet hydroformed Panel Front Door Outer. The doors were distributed in the same way as before amongst Lab 1a (9 doors) and Lab 1b (9 doors). All 18 doors were tested at Lab 2 later. Therefore, the results for the conventional stamped doors and the hydroformed doors should be comparable.

Structural testing was performed once again on the ULSAC DH door structure with a sheet hydroformed Panel Front Door Outer. Test set-up and results can be found in more detail in the Appendix.

5.1 Testing for Dent Resistance and Oil Canning

5.1.1 Details

All test results are shown in the test reports of Lab 1a and 1b and Lab 2. These reports can be found in the Appendix of this report. There is also a comparison made between the previous results for the stamped door outer panel and the hydroformed version. All graphs and diagrams are shown for both versions with a table comprised of the mechanical properties of the panels after forming and baking.

5.1.2 Conclusions

The quasi-static results reveal dent resistance for the hydroformed door panels that is quite similar to the dent resistance of the stamped doors. For most of the door variants the difference concerning critical dent load or remaining dent depth are just in the range of test accuracy.

The dynamic dent resistance results show the same relative behavior and ranking as the quasi-static results with slightly improved values due to the positive strain rate sensitivity of steel.

The oil canning behavior of hydroformed door outer panels differed significantly from the behavior of the stamped doors, particularly for the doors made from Dual Phase steel. There were occurrences of double oil canning which were common for many of the stamped doors. The overall oil canning behavior was improved with the hydroformed doors, although the centers of all hydroformed doors exhibited lower stiffness than their stamped counterparts. Thickness is the dominant factor for stiffness for a given part, design and material combination, since stiffness depends upon thickness raised to the power of three. Therefore, extended material thinning which goes together with stretching of the material may lead to a loss of stiffness.

With regards to dent resistance, this loss in thickness may be overcome by the increase of strength due to work hardening. All of the hydroformed door outer panels were thinner than their stamped counterparts, yet displayed essentially the same dent resistance because of the increased work hardening that occurred during the hydroforming process.

5.2 Final Material Selection for ULSAC DH Door Structure Hydroformed Door Outer Panel

The final material selection was made by a group including representatives from the ULSAC Consortium member companies who supplied the steel, testing companies, PES representatives and the ULSAC Program Director. All test results were taken into consideration.

Due to the fact that the DP 600 material in 0.6mm thickness has shown sufficient performance in oil canning and has met the requirements for static and dynamic dent resistance as well, this material was chosen for the door outer panels of the Demonstration Hardware. In the hydroformed panel, dent resistance of this material in the chosen thickness of 0.6mm was very similar to the values of the stamped variant, chosen earlier, of the BH 260 with a thickness of 0.7mm.

5.3 Testing for Structural Performance

To analyze the effect of the material thickness reduction from 0.7mm to 0.6mm for the ULSAC Panel Front Door Outer, the door structure was tested under the same conditions as described for the Demonstration Hardware with 0.7mm Door Outer Panels in the *ULSAC Engineering Report – April 2000*. The results show a slight increase in Vertical Door Sag performance and similar results for Upper and Lower Lateral Stiffness. The difference in results can be explained with door manufacturing tolerances and tolerances from test set-up and local effects. The results also confirm that the door design is not sensitive in respect to structural performance when changing the material thickness in the tested range.

Loadcase	ULSAC DH - Hydroformed	ULSAC DH - Stamped
Upper Lateral Stiffness Nm/deg	242	259
Lower Lateral Stiffness Nm/deg	203	261

Table 5.3-1 Upper and Lower Lateral Stiffness Results

	ULSAC DH - Hydroformed	ULSAC DH - Stamped
Vertical Door Sag Stiffness N/mm	181	157
Normalized Mass M_N kg/m_2	12.38	13.27

Table 5.3-2 Vertical Door Sag Stiffness Results

5.4 Mass of Door Structure

As a result of the reduction in material thickness from 0.7mm to 0.6mm, the mass of the ULSAC door structure was reduced. The assembled door structure with the 0.6mm nominal thickness sheet hydroformed Panel Front Door Outer was weighed at a mass of 9.68kg. This actual mass is slightly less than the calculated mass because, as shown in the Appendix reports, the in-part thickness of the door outer is thinner for the sheet hydroformed door outer than for the stamped door outer. To be conservative and to be consistent with economic analysis calculations in the next section, a door structure mass for comparison with the previous conventional stamped door was calculated. This was done by calculating the mass of the hydroformed door outer with a 0.6/0.7 ratio times the mass of the 0.6mm door outer panel and the resulting total mass of the door structure is 9.77kg. This mass results in a calculated normalized mass of 12.38kg/m^2.

The ULSAC Program targets were set as 12.23kg for the complete door structure and 15.50kg/m^2 for the normalized mass. Utilizing a 0.6mm Panel Front Door Outer manufactured with the AHM process, the ULSAC DH door structure performed better than the targets by 2.46kg and 3.12kg/m^2 respectively.

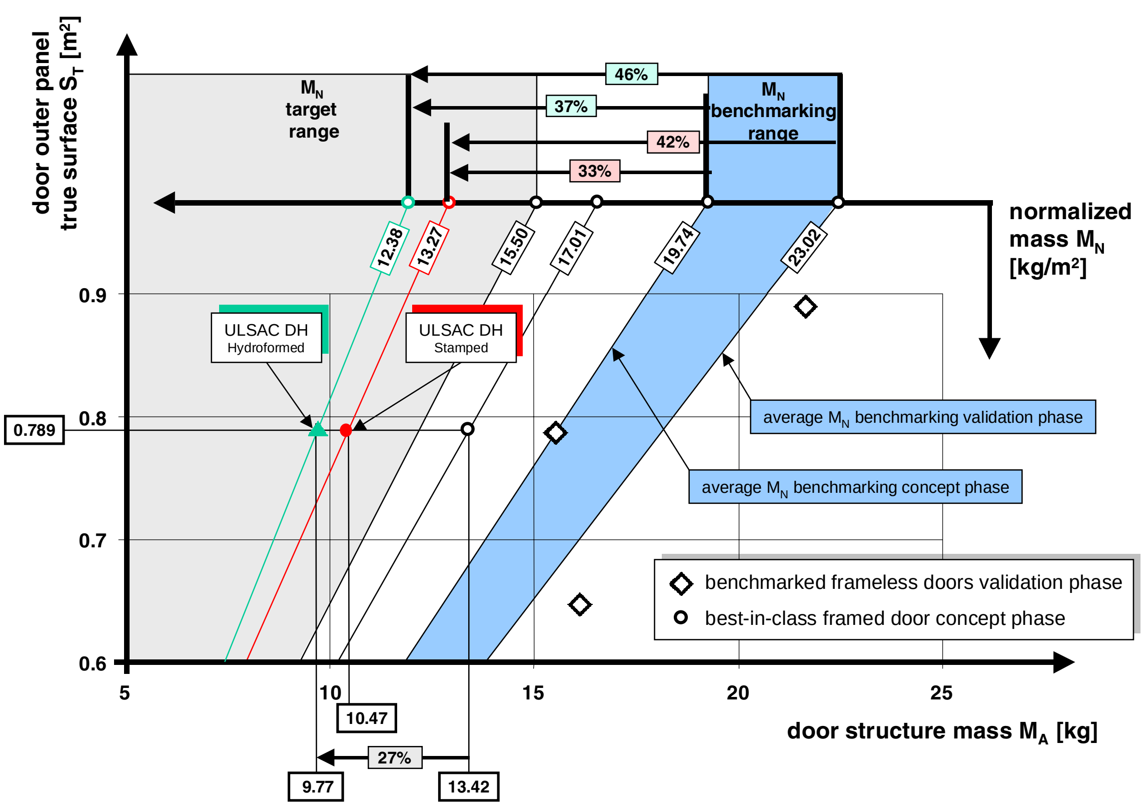


Figure 5.4-1 Result Summary

6 Economic Analysis

The objective was to establish a credible cost estimation for the ULSAC DH manufactured with the sheet hydroforming technology.

Background

As part of the ULSAC program, an economic analysis was undertaken to determine the manufacturing cost effectiveness of the proposed solution.

The objective of this program was to establish a credible cost estimation of the ULSAC door structure manufactured with the sheet hydroforming technology by using automotive practices of manufacturing engineering, process engineering and cost estimating.

To undertake this program, Porsche Engineering Services, Inc. (PES) organized an interactive process between product designers, sheet hydroforming process engineers and cost analysts. The team was comprised of the following organizations:

Porsche Engineering Services, Inc.	Program Management (incl. Validation)
Schuler SMG GmbH & Co. KG	Fabrication Process Engineering
Camanoe Associates / MIT	Cost Analysis

The goal was to allow end users the possibility to analyze "what-if" scenarios and compare the fabrication costs of the sheet hydroforming technology with the conventional stamping process. Therefore, the program used the technical cost model program developed by Camanoe Associates, a group of researchers of the Massachusetts Institute of Technology (MIT).

A similar approach and the identical cost model was used for modeling the ULSAC door structure published in the *ULSAC Engineering Report – April 2000*. Thus, all detailed information concerning the general cost modeling approach, the costs included and not included, as well as a description of the cost model structure, can be found there.

6.1 The Process of Cost Estimation

Identical general input assumptions were used for this approach. The basic assumptions are:

General Inputs	
Annual Production Volume	225,000
Working Days per Year	240
Production Location	Mid-West USA
Wage including benefits	44 $/h
Interest Rate	12%
Equipment Life	20
Production Life	5
Building Life	25
No. of Shifts	2

Table 6.1-1 Description of General Inputs

The ULSAC economic analysis for the sheet hydroformed Panel Front Door Outer began with the establishment of the basic assumptions regarding fabrication process engineering, which was solely provided by Schuler SMG in Waghaeusel Germany. Following validation by Porsche, as well as MIT, the data was then integrated into the cost model for final estimation.

The manufacturing line consists of a conventional blanking line, a hydraulic sheet hydroforming press, a laser cutting system, a washing facility for blanks and two additional small presses for flanging and piercing. Robots are integrated for transporting the semi-finished products from station to station.

Due to new concepts and technologies, Schuler SMG defined a cycle time of 30 seconds. The sheet hydroforming press (3,000 tons) has the controlling cycle time and can be broken down into:

Rapid approach and deceleration	~ 2 s
Pressure build-up blankholder	~ 2 s
Preforming and final forming	~ 15 s
Decompression	~ 1 s
Return of punch	~ 3 s
Remain in upper dead center position	~ 7 s

In order to avoid the need for higher forming pressures as explained in Chapter 4, PU-inserts are used. The first set of inserts including the steel fixtures are included in the tooling costs. Schuler SMG predicted that the lifetime of one PU-insert set would be approximately 100,000 hits and estimated costs for additional PU-insert sets to be approximately $500-700 each. This cost is negligible when compared to the overall investment in tools required to form the part and are therefore not included in the baseline analysis. However, they are part of discussion in the sensitivity analysis.

The subsequent trim of the hydroformed blanks will be done with a 3-dimensional laser cutting system with associated fixtures instead using traditional stamping methods which involve considerably higher initial investments in tooling. With maximum laser trim speeds of 10m/min, the entire trimming can be accomplished in 30 s, therefore matching the sheet hydroforming press cycle time.

	ULSAC 3000 Panel Door Outer RH	
	Sheet Hydroforming 0,6 mm / DP 600	Conventional Stamping 0,7 mm / BH 260
Blanking	Press Investment: $1,100,000 Coil Width: 1.300 mm Coil Progression: 1.000 mm	
Operations	#1: Sheet Hydroforming Die #2: Laser Trim #3: Cam Flange Die #4: Cam Flange and Pierce Die	#1: Draw Die #2: Trim+Pierce Die #3: Flange Die #4: Cam Flange Die #5: Cam Pierce and Trimming Die
Line Rate	30 s Cycle Time (~119 parts/h)	450 parts/hour
Tooling Investment	$530,000	$1,200,000
Line Investment	$5,100,000	$7,500,000 (ULSAB type A)

Table 6.1-2 Major Process Parameters

After finishing the laser trim operation, the parts will be run through a washing facility to clean the semi-finished panel of lubricant (sheet hydroforming operation) and metal dust (laser trim).

Figure 6.1-1 Manufacturing Line for Sheet Hydroforming Process

For the last two operations – flanging and piercing – small presses will be used. Schuler SMG proposed their single-action hydraulic press of two-upright design (type HPU 400-2000/2100). This press has a maximal slide capacity of 400 t and hydraulic clamping elements which are manually inserted in the T-slots of the bolster and slide plates and are shifted up to the clamping rim of the die. Additional hydraulic connections are provided in the die space to enable the use of bending and embossing punches in the integrated die. They are powered by a separate hydraulic power unit on the press which is designed for larger oil volume. The design of this press type does not require a pit for press installation. The press is fixed by suitable foundation bolts.

6.2 ULSAC Panel Front Door Outer Cost Results

The cost analysis of the sheet hydroforming technology is presented in the following, and corresponds to the conventional stamped ULSAC Panel Front Door Outer discussed in the *ULSAC Engineering Report – April 2000*.

The sheet hydroformed panel which is discussed uses DP 600 with a materials thickness of 0.6mm.

	ULSAC 3000 Panel Door Outer RH			
	Sheet Hydroforming 0,6 mm / DP 600		Conventional Stamping 0,7 mm / BH 260	
Total Variable Costs	**$7.87**	55.7%	**$6.66**	64.0%
Material	$5.98	42.4%	$5.96	57.3%
Labor	$1.62	11.4%	$0.50	4.8%
Energy	$0.27	1.9%	$0.20	1.9%
Total Fixed Costs	**$6.25**	44.3%	**$3.75**	36.0%
Equipment	$3.59	25.4%	$1.59	15.3%
Tooling	$0.65	4.6%	$1.48	14.2%
Building	$0.08	0.6%	$0.05	0.5%
Overhead Labor	$1.49	10.6%	$0.32	3.1%
Maintenance	$0.43	3.1%	$0.31	3.0%
Part Fabrication Costs	**$14.13**	100.0%	**$10.41**	100.0%
Part Weight	**4.177 kg**		**4.873 kg**	

Table 6.2-1 Sheet Hydroforming Technology Cost Results

The material costs, compared to the stamped door outer, are almost identical. Reduced cost due to less material weight is offset by higher costs of the DP600.

Labor costs, as well as equipment costs, directly depend on the cycle time. The higher cycle times associated with the sheet hydroforming process result in higher labor and equipment costs over the conventional stamping.

Tooling costs are independent of the cycle time. They depend only on the initial investment, annual production volume and the production life. Thus, with lower tooling investments, due to the saved bottom die during the sheet hydroforming operation and saved trim die during the laser trim operation, the tooling costs per part are reduced.

6.3 Sensitivity Analysis

An important element of the technical cost modeling approach is to determine the potential effect of changes in the process variables on the resulting cost. This is often discussed as sensitivity or scenario analysis.

Especially for this new technology where process parameters are only partly based on a long-term experience of a series production, it is important to validate the influence of uncertainties in these parameters.

Therefore, the following investigations concerning sensitivity were defined and discussed.

6.3.1 Cycle Time

The cycle time for the whole process was discussed for 20 s and 60 s in comparison with the base scenario of 30 s.

By looking at 60 s, 146% of the line was needed, which led to the assumption that a second set of tooling was considered.

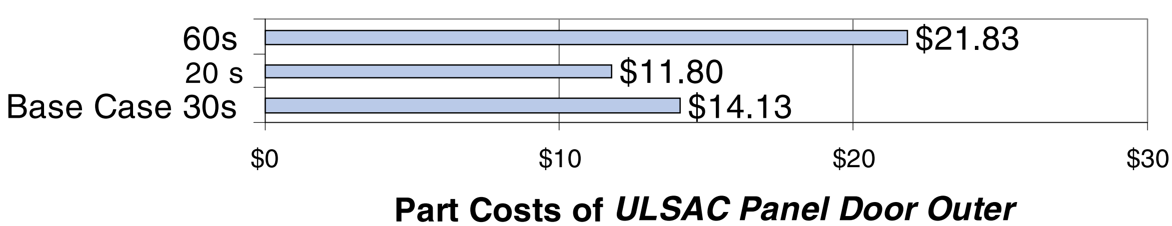


Figure 6.3.1-1 Sensitivity of Cycle Time

6.3.2 Blank Size

Sensitivity of the blank size was discussed. Only changes in the material cost were considered since a marginally larger blank could still be accommodated on the same production equipment.

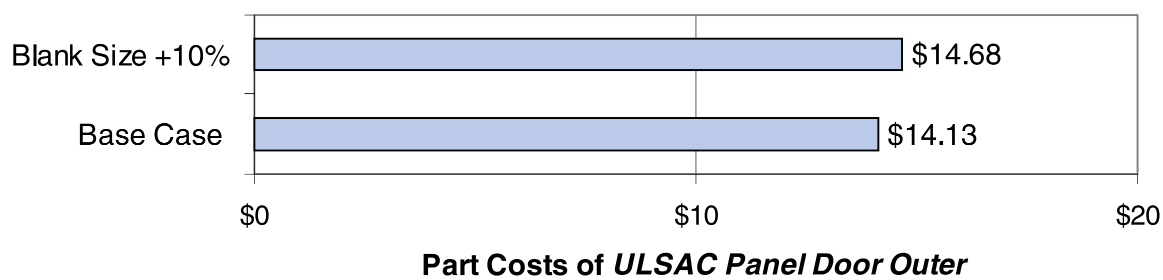


Figure 6.3.2-1 Sensitivity of Blank Size

6.3.3 Lifetime of PU-insert

The lifetime of the PU-inserts in the sheet hydroforming tooling is a rather large unknown. By considering the reject rate, a total of 1,159,560 hits (5 years *231,912 hydroforming hits) is necessary.

The costs of these inserts are very small compared with the remaining tooling costs and therefore, the effect is minimal. However, to demonstrate this effect, PU-insert life is allowed to vary dramatically in this sensitivity analysis. Even these large changes resulted in only insignificant cost increases which are shown in following figure.

	Base Case	Variation 1	Variation 2
Lifetime [No. of hits]	100,000	10,000	3,000
Additional PU-inserts neede	11	115	386
Additional Tooling Costs ($700 per insert)	$0	$80,000	$270,000

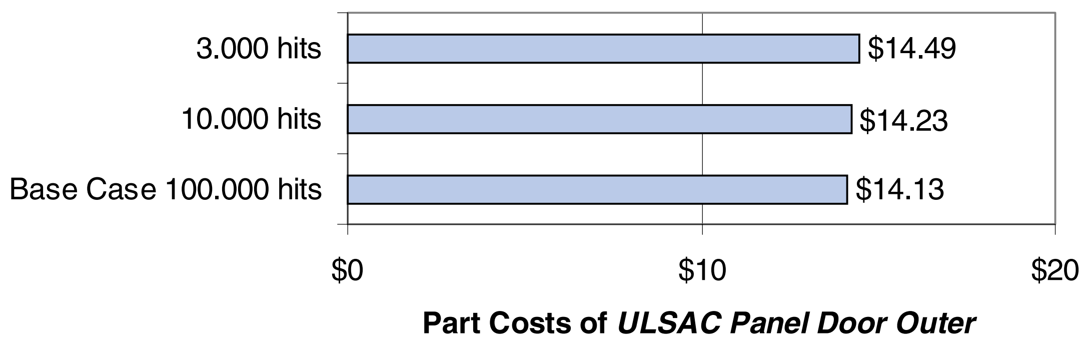


Figure 6.3.3-1 Sensitivity of Lifetime of PU-inserts

6.3.4 Annual Production Volume

Additionally, the sensitivity of the annual production volume for the ULSAC Panel Front Door Outer was discussed for sheet hydroforming as well as for conventional stamping.

The diagram shows that the break-even volume for sheet hydroforming can be found in the region of 45,000 units/year.

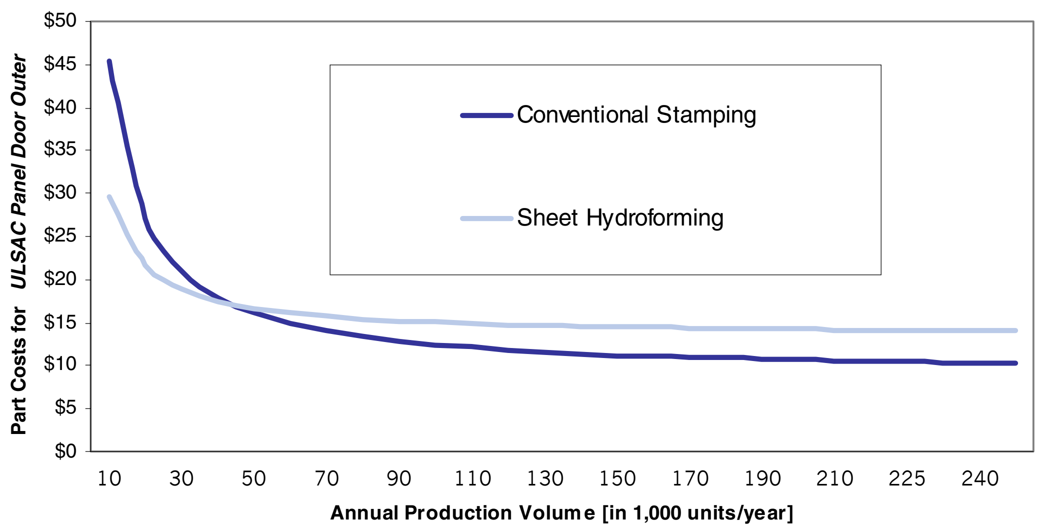


Figure 6.3.4-1 Sensitivity of Annual Production Volume

6.4 Conclusion

The results of the economic analysis of the ULSAC Panel Front Door Outer utilizing the sheet hydroforming process are $3.72 higher than the costs of the similar conventional stamped panel, assuming an annual production volume of 225,000 units/year.

For that increase in cost, a 0.7kg mass reduction for the Panel Front Door Outer has been achieved.

The high cycle time of the sheet hydroforming process, which is nearly 4 times higher than the conventional stamped cycle time, leads to an increase in equipment and labor costs. They cannot be compensated through enormous savings in tooling costs for the new process.

Reduced cycle time for sheet hydroforming is also a key to making the process more competitive.

It was shown that for smaller production volumes, sheet hydroforming becomes more and more cost competitive because the influences of the tooling costs become greater and greater.

Part Weight	Part Costs
- 0.7 kg	+ $ 3.72

ULSAC Amendment Report
Appendix Table of Contents

1. ULSAC Panel Front Door Outer Tryout Logs

Protokoll

Project:	**ULSAC outer door panel**	Auftragsnr. 770098000	
Prototyping at:	13:07		
Time	17:00		
Workers:	Dr. Kolleck / Formanski		

Material / blank:

Description:	BH210	Sheet thickness:	0.6	measured sheet thickness	0.58
blank size:	1800/1250	blank cut:	blank outline as FE computing result		

Process data

Preforming	volume flow / pressure intensifier 250 mm		
Preform-pressure	ca. 0,4 MPa	Punch position	100 mm over the blank
Blankholder force	2000 to		
Preformdirection	AHM		

Hydromechanical deep drawing:

Blankholderforce	300 to	Pressure:	9 MPa
Drwaing depth	140 mm		

Calibration

Max. Presssure	15 MPa

Friction:

drawing oil

RAZIOL CLF 250 F

Picture / Remarks

Results: Raising the pressure on 15 MPa lead to the best forming of the surface.

Protokoll

Project:	**ULSAC outer door panel**	Auftragsnr. 770098000
Prototyping at:	13:07	
Time	15:00	
Workers:	Dr. Kolleck / Formanski	

Material / blank:

Description:	ZStE 210 bh	Sheet thickness:	0.7	measured sheet thickness	0.65
blank size:	1800/1250	blank cut:	blank outline as FE computing result		

Process data

Preforming	volume flow / pressure intensifier 250 mm		
Preform-pressure	ca. 0,5 MPa	Punch position	100 mm over the blank
Blankholder force	2000 to		
Preformdirection	AHM		

Hydromechanical deep drawing:

Blankholderforce	300 to	Pressure:	9 MPa
Drwaing depth	140 mm		

Calibration

Max. Presssure	15 MPa

Friction:

drawing oil

RAZIOL CLF 250 F

Picture / Remarks

Results: Raising the pressure on 15 MPa lead to the best forming of the surface.

Protokoll

Project:	**ULSAC outer door panel**	Auftragsnr. 770098000	
Prototyping at:	12:07		
Time	19:00		
Workers:	Dr. Kolleck / Formanski		

SCHULER SMG

Material / blank:

Description:	ZStE 260 bh	Sheet thickness:	0.6	measured sheet thickness	0.58
blank size:	1800/1250	blank cut:	blank outline as FE computing result		

Process data

Preforming	volume flow / pressure intensifier 250 mm		
Preform-pressure	ca. 0,6 MPa	Punch position	100 mm over the blank
Blankholder force	2000 to		
Preformdirection	AHM		

Hydromechanical deep drawing:

Blankholderforce	400 to	Pressure:	9 MPa
Drawing depth	140 mm		

Calibration

Max. Presssure	15 MPa

Friction:

drawing oil

RAZIOL CLF 250 F

Picture / Remarks

Results: Raising the pressure on 15 MPa lead to the best forming of the surface.

Protokoll

Project:	**ULSAC outer door panel**	Auftragsnr. 770098000	
Prototyping at:	15:07		
Time	20:00		
Workers:	Dr. Kolleck / Formanski		

Material / blank:

Description:	ZStE 260 bh	Sheet thickness:	0.7	measured sheet thickness	0.7
blank size:	1800/1250	blank cut:	blank outline as FE computing result		

Process data

Preforming	volume flow / pressure intensifier 250 mm		
Preform-pressure	ca. 0,7 MPa	Punch position	100 mm over the blank
Blankholder force	2000 to		
Preformdirection	AHM		

Hydromechanical deep drawing:

Blankholderforce	600 to	Pressure:	9 MPa
Drwaing depth	140 mm		

Calibration

Max. Presssure	15 MPa

Friction:

drawing oil

RAZIOL CLF 250 F

Picture / Remarks

Results: Raising the pressure on 15 MPa lead to the best forming of the surface.

Protokoll

Project:	**ULSAC outer door panel**	Auftragsnr. 770098000
Prototyping at:	13:07	
Time	19:00	
Workers:	Dr. Kolleck / Formanski	

Material / blank:

Description:	DP 600	Sheet thickness:	0.6	measured sheet thickness	0.58
blank size:	1800/1250	blank cut:	blank outline as FE computing result		

Process data

Preforming	volume flow / pressure intensifier 250 mm		
Preform-pressure	ca. 0,8 MPa	Punch position	115 mm over the blank
Blankholder force	2000 to		
Preformdirection	AHM		

Hydromechanical deep drawing:

Blankholderforce	500 to	Pressure:	9 MPa
Drwaing depth	140 mm		

Calibration

Max. Presssure	18 MPa

Friction:

drawing oil

RAZIOL CLF 250 F

Picture / Remarks

Results: Raising the pressure on 18 MPa lead to the best forming of the surface.

Protokoll

Project:	**ULSAC outer door panel**	Auftragsnr. 770098000
Prototyping at:	15:07	
Time	16:00	
Workers:	Dr. Kolleck / Formanski	

Material / blank:

Description:	DP 600	Sheet thickness:	0.7	measured sheet thickness	0.7
blank size:	1800/1250	blank cut:	blank outline as FE computing result		

Process data

Preforming	volume flow / pressure intensifier 250 mm		
Preform-pressure	ca. 1 MPa	Punch position	100 mm over the blank
Blankholder force	2000 to		
Preformdirection	AHM		

Hydromechanical deep drawing:

Blankholderforce	600 to	Pressure:	9 MPa
Drwaing depth	140 mm		

Calibration

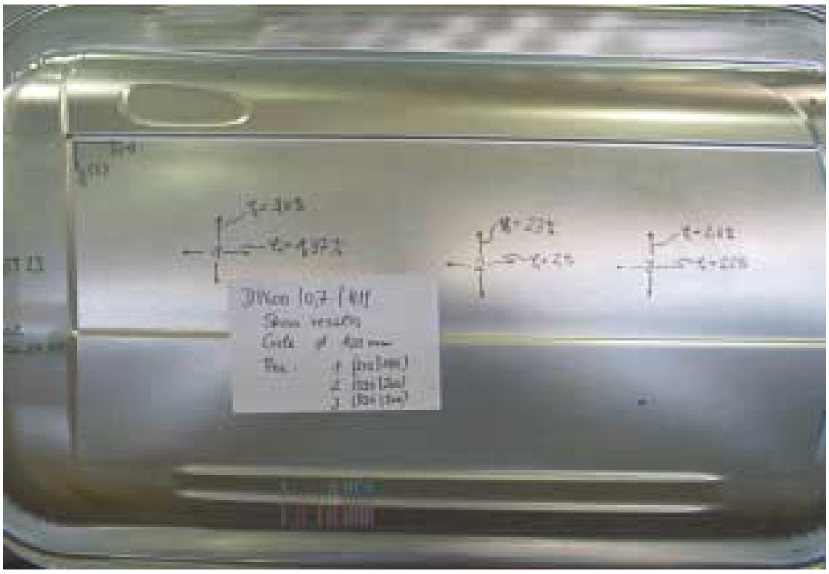
Max. Presssure	20 MPa

Friction:

drawing oil

RAZIOL CLF 250 F

Picture / Remarks



Results: Raising the pressure on 20 MPa lead to the best forming of the surface.

2. Forming Simulation

ULSAC Panel Front Door Outer Forming Simulation

3. Dent Resistance and Oil Canning Report

Dent Resistance and Oil Canning Reports

This section contains five reports:

(Initial Tests – October / November 2000)

1. Lab 1a & 1b – Report – 16 Nov 2000
   Dynamic Dent Testing of Hydroformed ULSAC Doors at Lab 1a & 1b
2. Lab 2 Report – 07 Nov 2000
   Results of Dent Testing of Hydroformed ULSAC Doors
3. Lab 2 – Material Properties – 27 Oct 2000

(Additional Tests – December 2000)

4. Lab 2 – Report – 14 Dec 2000
   Dent Test Results for Three Hydroformed Electrogalvanized Dual Phase 600 Doors for the ULSAC Program
5. Lab 2 – Material Properties – 14 Dec 2000

Conclusions from October / November 2000 Reports:

- The hydroformed ULSAC doors exhibited approximately the same dent resistance as the stamped ULSAC doors.
- The hydroformed ULSAC doors exhibited improved oil-canning performance compared with the stamped ULSAC doors.
- The dynamic dent resistance of the hydroformed ULSAC doors was approximately the same as for the stamped ULSAC doors.

Actions taken as a result of October / November Reports:

A group consensus decision was made to use 0.6mm DP600 steel grade outers for the sheet hydroformed doors. The following factors were considered in this decision:

- Active Sheet Hydroforming is one means to reduce the gauge of outer panels and thus reduce mass
- Both 0.60mm BH260 and DP600 exhibited sufficient dent resistance whereas 0.60mm BH210 did not exhibit sufficient dent resistance.
- Oil canning performance of DP600 was better than BH260. Surface quality of the original 0.6mm DP600 was not sufficient for display doors. Therefore, door outers for display should be produced from material of the same base metal grade with suitable surface quality. Additional doors would be produced from available EG DP600 0.6mm material and tested.

Conclusions from December 2000 Reports:

The EG DP600 0.6 mm doors exhibited slightly improved dent resistance over the GI DP600 0.6mm doors and confirmed that the same base metal grade performed essentially the same in dent resistance. Mild oil canning was evident in all three EG doors and in one of the GI DP600 0.6 mm doors. Oil canning of both the GI and EG DP600 0.6mm hydroformed door outers was mild as compared to “hard” oil canning exhibited in GI DP600 0.6mm stamped door outers.

Summary - Dent Resistance and Oil Canning Reports

DP600 material in 0.6mm thickness was chosen for the door outer panels of the demonstration hardware (DH) because it met the requirements for static and dynamic dent resistance and has shown sufficient performance in oil canning as well. Dent resistance of the 0.6mm DP600 sheet hydroformed door outer was very similar to the values of the 0.7mm BH260 stamped door outer, chosen for the first set of DH in April 2000.

Targets for quasi-static and dynamic dent resistance were described (in the April 2000 Engineering Report). The North American Auto/Steel Partnership criteria for evaluating dent resistance is used in this project. For example, quasi-static dent resistance is defined as “excellent” with a critical dent load of 150N for a 0.1mm dent and a critical dent load of 130N for a 0.1mm dent is defined as “acceptable”.

The quasi-static results reveal dent resistance for the hydroformed door panels that is quite similar to the dent resistance of the stamped doors. For most of the door variants, the differences concerning critical dent load or dent depth are in the range of test accuracy.

The dynamic dent resistance results show the same relative behavior and ranking as the quasi-static results with slightly improved values due to steel’s positive strain rate sensitivity.

The oil canning behavior of hydroformed door outer panels differed significantly from the behavior of the stamped doors, particularly for the doors made from Dual Phase steel. Common for many of the stamped doors were occurrences of double oil canning. The overall oil-canning behavior was improved with the hydroformed doors, although the centers of all hydroformed doors exhibited lower stiffness than their stamped counterparts. This is related to the fact that thickness is the dominant factor for stiffness for a given part, design and material combination. Therefore, material thinning, which naturally coincides with material stretching, may lead to a loss of stiffness.

With regard to dent resistance, this loss in thickness may be overcome by the increase of strength due to work hardening. All of the hydroformed door outer panels were thinner than their stamped counterparts, yet displayed essentially the same dent resistance because of the increased work hardening that occurred during the hydroforming process.

Lab 1a & 1b – Report – 16 Nov 2000

Dynamic dent testing of hydrofromed ULSAC doors at Lab 1a & 1b

Introduction

Within the ULSAC project, doors have been made from a range of steel grades. Examination of the performance of these doors (e.g. static and dynamic denting, oil canning and stiffness) was required. Of all the ULSAC members, only Lab 1 is able to conduct dynamic dent tests on panels or products. The ULSAC members decided that Lab 1a (IJTC) and Lab 1b (WTC) should determine the dynamic dent resistance of the doors.

In a previous report [3], a comparison was made between different steel grades with respect to the dynamic dent resistance of stamped doors. In this report the same grades of steel are tested but the doors were hydroformed.

Eighteen doors (two thickness', three materials and one production technique), hydroformed for the ULSAC project, have been tested. There were three replica doors for each set of variables. IJTC and WTC received one or two of each type of door for dynamic dent testing.

Conclusion & Recommendations

The results in this report are **only** valid for the particular ULSAC door geometry and at the tested locations. Thickness, strain and geometry have a large influence on the dynamic dent resistance.

The measured thicknesses of the hydroformed doors are less or equal than the stamped doors. The thickness strain in the middle of the outer panel is higher if hydroforming is used.

The dynamic dent resistance does not appear to be influenced by the hydroform forming process. The BH210 door (0.6 mm) is the only combination of material and thickness of which the dynamic dent resistance appears to be influenced at all by the forming process, when comparing hydroforming with stamping.

It is known that the influence of thickness on dent depth after dynamic (impact) denting is larger than the influence of yield strength. In both sets of tests (WTC and IJTC, hydroformed and stamped) the dent depth relating to BH210 with a thickness of 0.7 mm is comparable to the dent depth of DP600 with a thickness of 0.6 mm.

Materials

Three materials were selected for in-service dynamic dent resistance testing. The materials chosen were BH220, BH260 and DP600. All three materials were at two thicknesses: 0.6 and 0.7 mm thick.

Procedure

The procedure used was the same as used in testing the stamped ULSAC doors and is described in [3]. Each door was tested on two points indicated on the door plans (figure 1). These locations are at the following co-ordinates:

1. X = 2950 mm and Z = 770 mm (*right*)
2. X = 2350 mm and Z = 770 mm (*left*)

At IJTC, the kinetic energy of the bullets was 1 J (± 47.6 m/s); at WTC, the impact velocity of the bullet was approximately 50 mph, (± 22.3 m/s and ± 5.9 J)

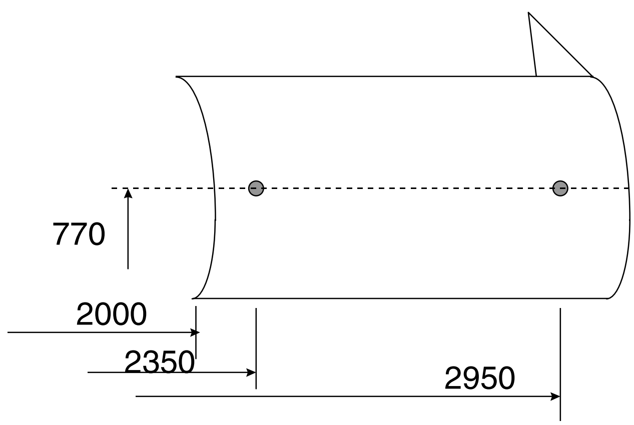


Figure 1: Locations of denting

Test results

Thickness measurements

All the doors were dented at two locations. At Lab 2 the thicknesses were measured in the middle of the panels. In figures 4 & 5 the original thickness [ref 3] and the measured thickness' of stamped and hydroformed doors are given. The thicknesses of the hydroformed doors are less than or comparable to the thicknesses of the stamped doors.

Dynamic dent test results

All the doors were dented at two locations. In figure 2 & 3 and tables 1 & 2 the results of the dynamic dent tests are given.

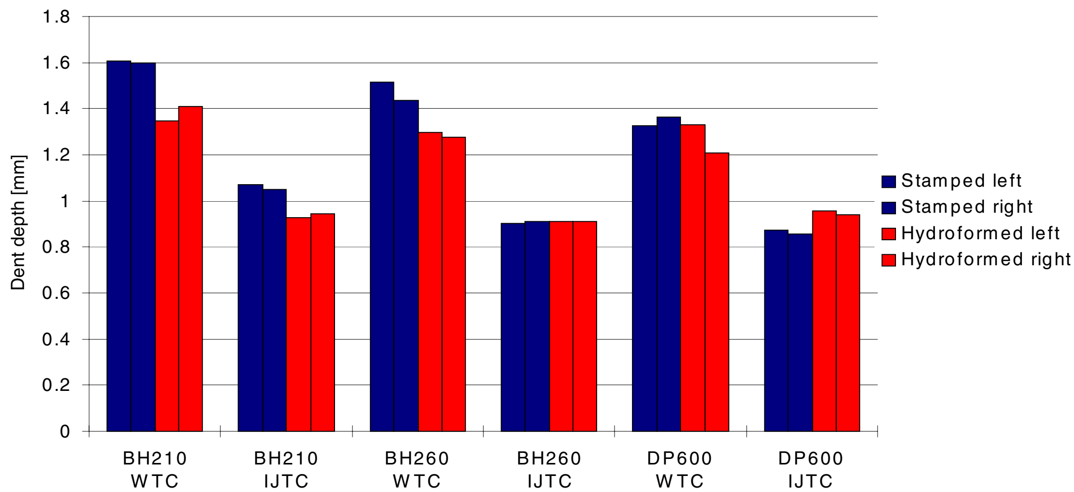


Figure 2: Results of the dynamic dent tests of WTC and IJTC (thickness 0.6 mm)

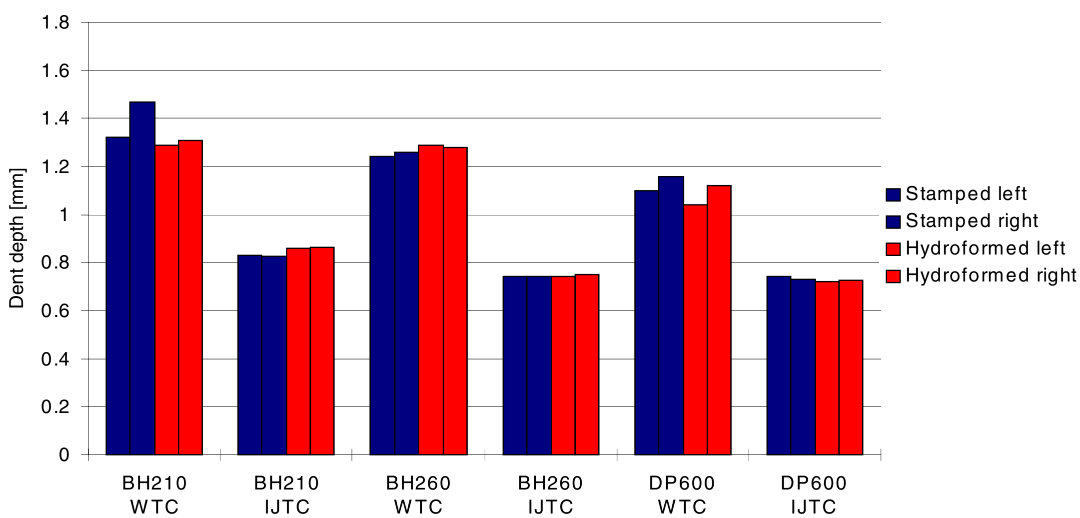


Figure 3: Results of the dynamic dent tests of WTC and IJTC (thickness 0.7 mm)

The much deeper dents measured by WTC, compared with those measured by IJTC, is as a result of denting with much a larger bullet at lower velocity. This conclusion was drawn from earlier tests on flat panels [1 & 2].

It is known that the thickness and the geometry of the panel have a large influence on dent depth. The results in this report are **only** valid for the particular ULSAC door geometry at the tested locations.

From figures 2 & 3 the conclusion can be drawn that dynamic dent resistance is not influence by the hydroforming process. The dynamic dent resistance of the stamped doors is almost equal to the dynamic dent resistance of the hydroformed doors. The BH210 door (0.6 mm) is the only combination of material and thickness for which the dynamic dent resistance is noticeably influenced by the forming process, when comparing hydroforming to stamping.

The influence of thickness on dent depth is larger than the influence of yield strength. In both sets of tests (WTC and IJTC, hydroformed and stamped) the dent depth relating to BH210 with a thickness of 0.7 mm is comparable to the dent depth of DP600 with a thickness of 0.6 mm.

References

1. Round robin dynamic dent reistance with (company name); results (company name) part, Roelofsen/Botman, Arch.lab.nr 101861, 1 september 1999
2. Round robin dynamic dent resistance testing results, Elliott, report no. WL/PE/TA4/T03/4/2000/D, File No 1627, 7/1/2000
3. Dynamic dent testing of ULSAC doors at (company name), Elliott/vStijn, Arch.lab.nr. 102834, February 16 2000

ID code	dd long *left*	dd trans *left*	dd long *right*	dd trans *right*
BH210/0.6/HM/1	0.918	0.939	0.937	0.952
BH210/0.7/HM/3	0.841	0.860	0.860	0.865
BH210/0.7/HM/4	0.857	0.886	0.588	0.597
BH260/0.6/HM/1	0.897	0.924	0.908	0.913
BH260/0.7/HM/3	0.750	0.761	0.749	0.752
BH260/0.7/HM/6	0.721	0.747	0.740	0.758
DP600/0.6/HM/2	0.950	0.964	0.925	0.952
DP600/0.7/HM/3	0.702	0.728	0.716	0.719
DP600/0.7/HM/4	0.715	0.742	0.736	0.736

Table 1: Measured dent depths at IJTC in longitudinal and transverse direction of the doors

Material	WTC ID	dd *left*	dd *right*
BH220/0.6/HM/2	PEF0024/23	1.37	1.46
BH220/0.6/HM/3	PEF0024/22	1.32	1.36
BH220/0.7/HM/5	PEF0024/24	1.29	1.31
BH260/0.6/HM/2	PEF0024/16	1.31	1.24
BH260/0.6/HM/4	PEF0024/18	1.28	1.31
BH260/0.7/HM/1	PEF0024/17	1.29	1.28
DP600/0.6/HM/1	PEF0024/21	1.36	1.28
DP600/0.6/HM/2	PEF0024/20	1.30	1.14
DP600/0.7/HM/5	PEF0024/19	1.04	1.12

Table 2: Measured dent depths at WTC

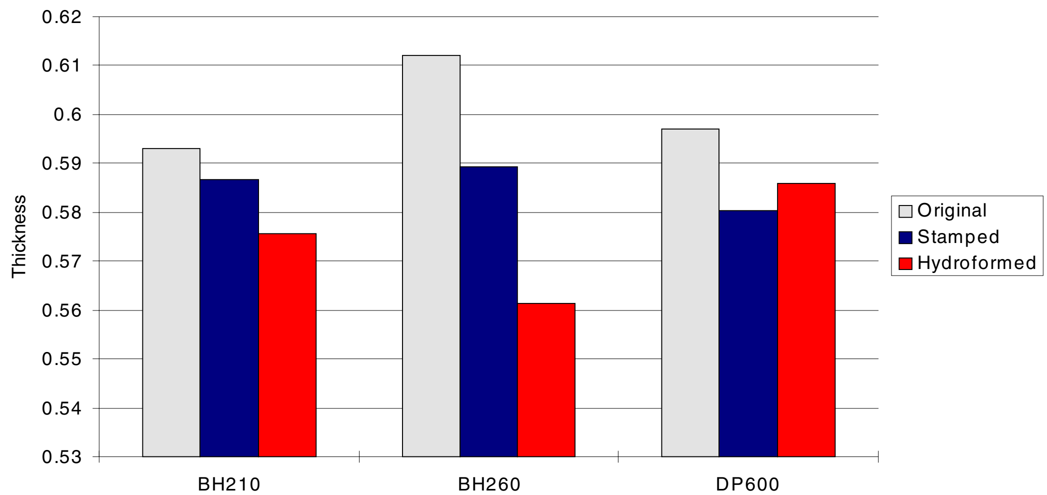


Figure 4: Thickness measurements of the doors by Lab 2 (thickness 0.6 mm)

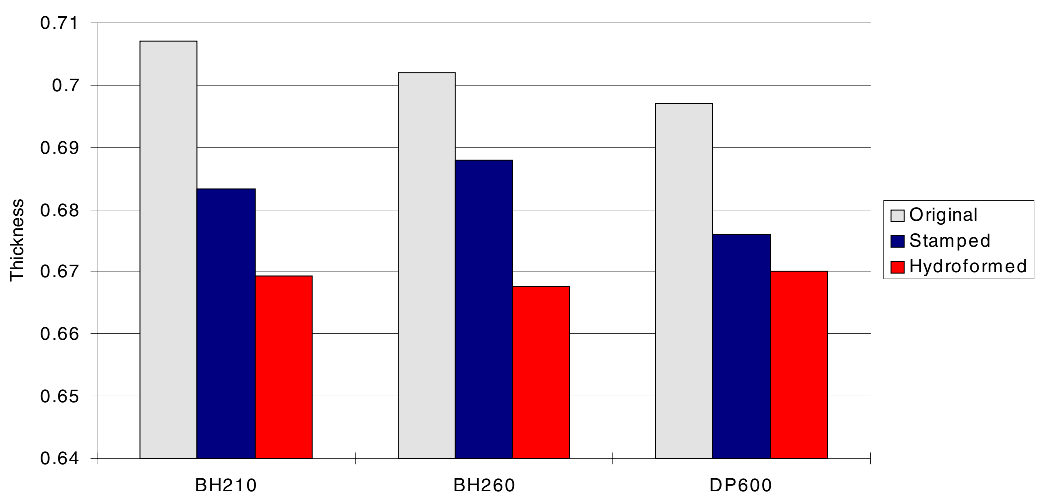


Figure 5: Thickness measurements of the doors by Lab 2 (thickness 0.7 mm)

Lab 2 Report - 07Nov2000

Results of Dent Testing of Hydroformed ULSAC Doors (WO 4334)

Eighteen ULSAC doors with sheet-hydroformed outer panels were dent tested at Lab 2. The doors represented combinations of three outer skin materials (BH210, BH260, and DP600) at two thicknesses (0.6mm and 0.7mm). The denting behaviors of theses doors were compared with identical door outers made from the same materials which were stamped rather than hydroformed. Quasi-static dent resistance, dynamic dent resistance, and the quasi-static load - deflection curve were determined for each door at specified locations. The doors exhibited virtually identical dent resistance when compared with the stamped doors in both quasi-static and dynamic testing. The oil-canning behavior was significantly improved in the hydroformed doors compared with the stamped doors, although the centers of all of the doors exhibited very low stiffness. Increased thickness and increased panel strength contributed to better dent resistance and better oil-canning behavior in the panels tested. All material/thickness combinations exhibited adequate dent resistance (greater than 130N for a 0.1-mm dent), and all but the 0.6mm BH210 exhibited superior dent resistance (150 N or greater).

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Introduction

Eighteen assembled steel doors with sheet-hydroformed outer panels, provided by the Ultra-Light Steel Auto Closures (ULSAC) program, were dent tested at the Lab 2. The door outers were made from three strength levels steel (BH210, BH 260, and DP600), each at two thicknesses (0.6mm and 0.7mm). There were three doors for each strength-level – thickness combination.

All of the doors had indentations in the central region of the door where Lab 1 had previously performed dynamic impact tests (1).

Dent testing was performed on the Lab 2 dent tester using the Auto/Steel Partnership (A/SP) draft procedure (2). This procedure consists of a quasi-static incremental dent test, which yields a dent load – dent depth relationship. A quasi-static fixed load test and dynamic (250mm/s) incremental tests were also performed on each door.

Results were compared with testing of identical doors with stamped outers tested earlier in the year (3).

Procedure

The procedure used was described in the report of the previous testing (3). A critical dent depth of 0.1mm was used for the quasi-static and dynamic testing. The locations tested are presented in Figure 1.

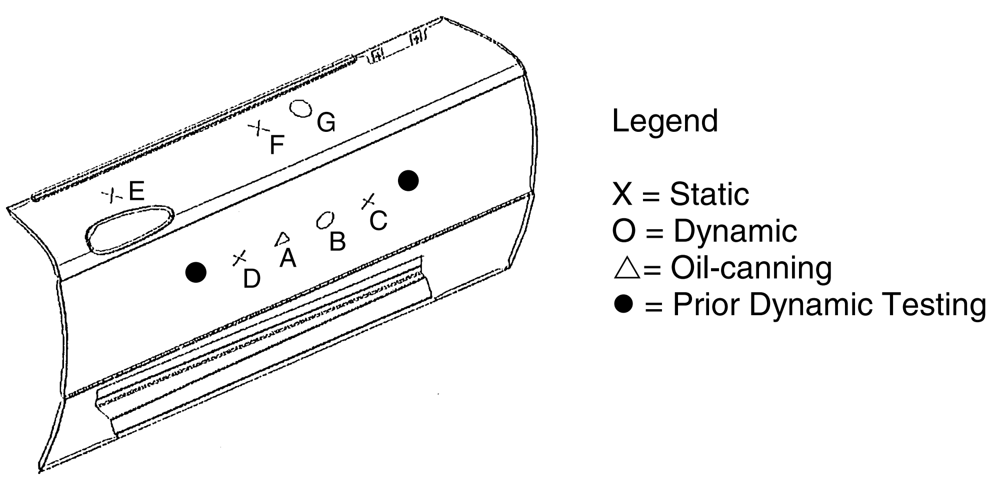

Figure 1. Test locations.

Results

Quasi-Static Incremental Testing

The results of the quasi-static incremental dent tests are given in table 1.

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Table I. Quasi-Static Incremental Dent Test Results								
	Location C		Location D		Location E		Location F	
Panel	Stiffness (N/mm)	Critical Dent Load at 0.1 mm Dent Depth (N)	Stiffness (N/mm)	Critical Dent Load at 0.1 mm Dent Depth (N)	Stiffness (N/mm)	Critical Dent Load at 0.1 mm Dent Depth (N)	Stiffness (N/mm)	Critical Dent Load at 0.1 mm Dent Depth (N)
BH210-0.6*	13	139	15	136	25	150	35	144
BH210-0.7*	21	148	19	140	39	137	52	142
BH260-0.6*	14	139	15	143	18	139	34	140
BH260-0.7	15	146	18	156	39	174	56	155
DP600-0.6*	11	150	11	145	25	144	33	164
DB600-0.7	18	240	21	220	41	220	29	222

*Hard oil-canning in panel

Quasi-Static Single Load Testing
Hard oil-canning, marked by a drop in load on the load – deflection curve from single increment, fixed load testing, occurred in the locations marked. All panels displayed "soft" oil-canning, which is the presence of an inflection point in the load – deflection curve. Those panels displaying some hard oil-canning are indicated with an asterisk in the panel column of table I.

Dynamic Incremental Dent Testing
The dynamic incremental test results are given in table II.

Table II. Dynamic Incremental Dent Test Results		
	Critical Dent Load at 0.1 mm Dent Depth (N)	
Panel	Location B	Location G
BH210 - 0.6	180	176
BH210 - 0.7	196	166
BH260 - 0.6	176	174
BH260 - 0.7	209	189
DP600 - 0.6	198	208
DB600 - 0.7	297	271

Discussion

Oil-canning
The oil-canning behavior of the hydroformed doors differed significantly from the behavior of the stamped doors, particularly for the doors made from the higher strength steels. The load - deflection curves for the fixed load tests on the hydroformed doors are given in figure 2; the curves from the stamped doors are given in figure 3. There was no occurrence of double oil-canning in the hydroformed doors, a phenomenon that was common in the stamped doors. The thicker BH260 and DP600 hydroformed doors displayed no hard oil-canning, although the panels were still quite soft. The 0.7mm DP600 hydroformed doors had the best oil-canning behavior overall.

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Figure 2. Load – Deflection curves for hydroformed doors.

210BH 0.6 mm Location A Fixed Load Test | 210BH 0.7 mm Location A Fixed Load Test

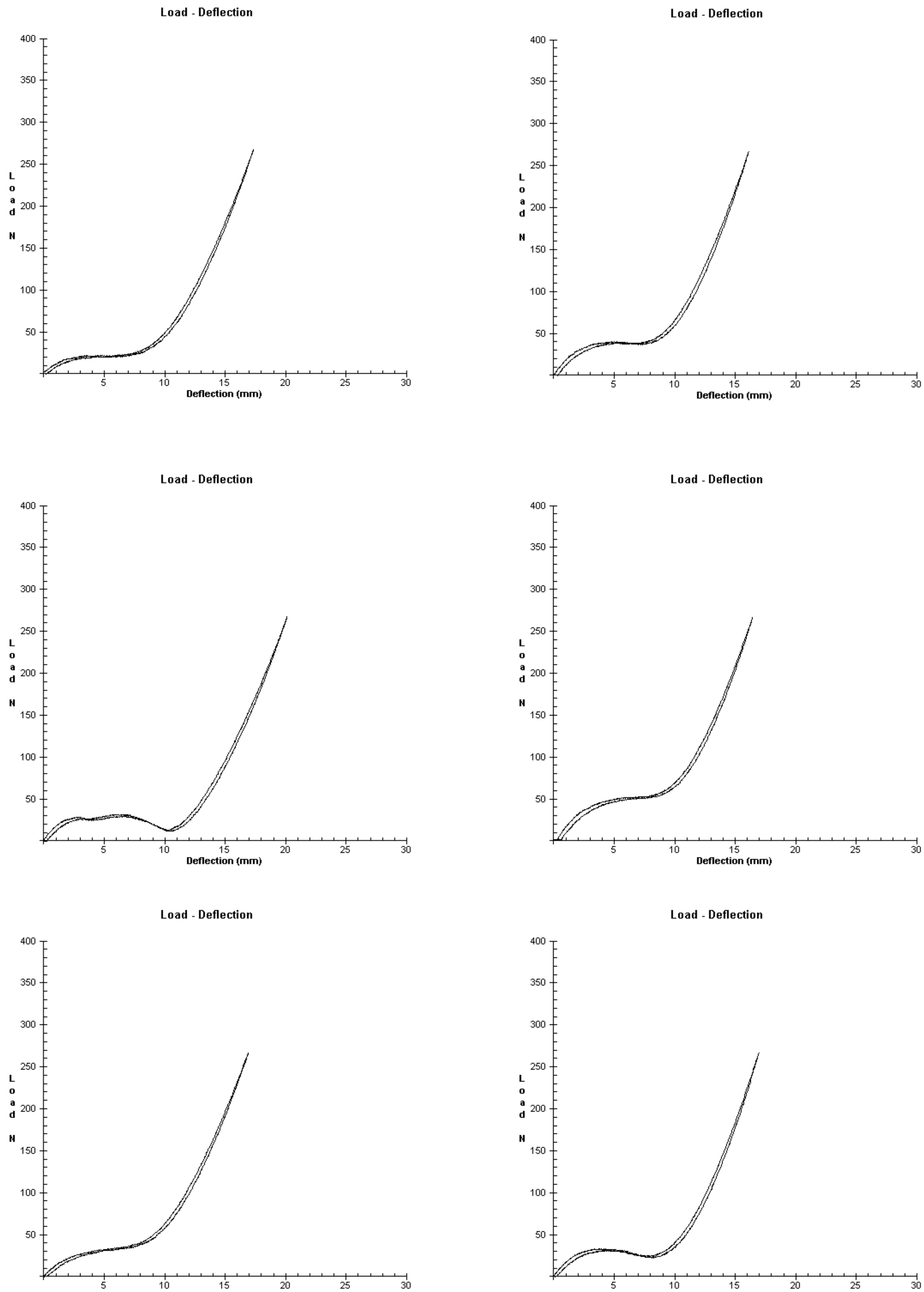

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Figure 2. Load – Deflection curves for hydroformed doors.

260BH 0.6 mm Location A Fixed Load Test | 260BH 0.7 mm Location A Fixed Load Test

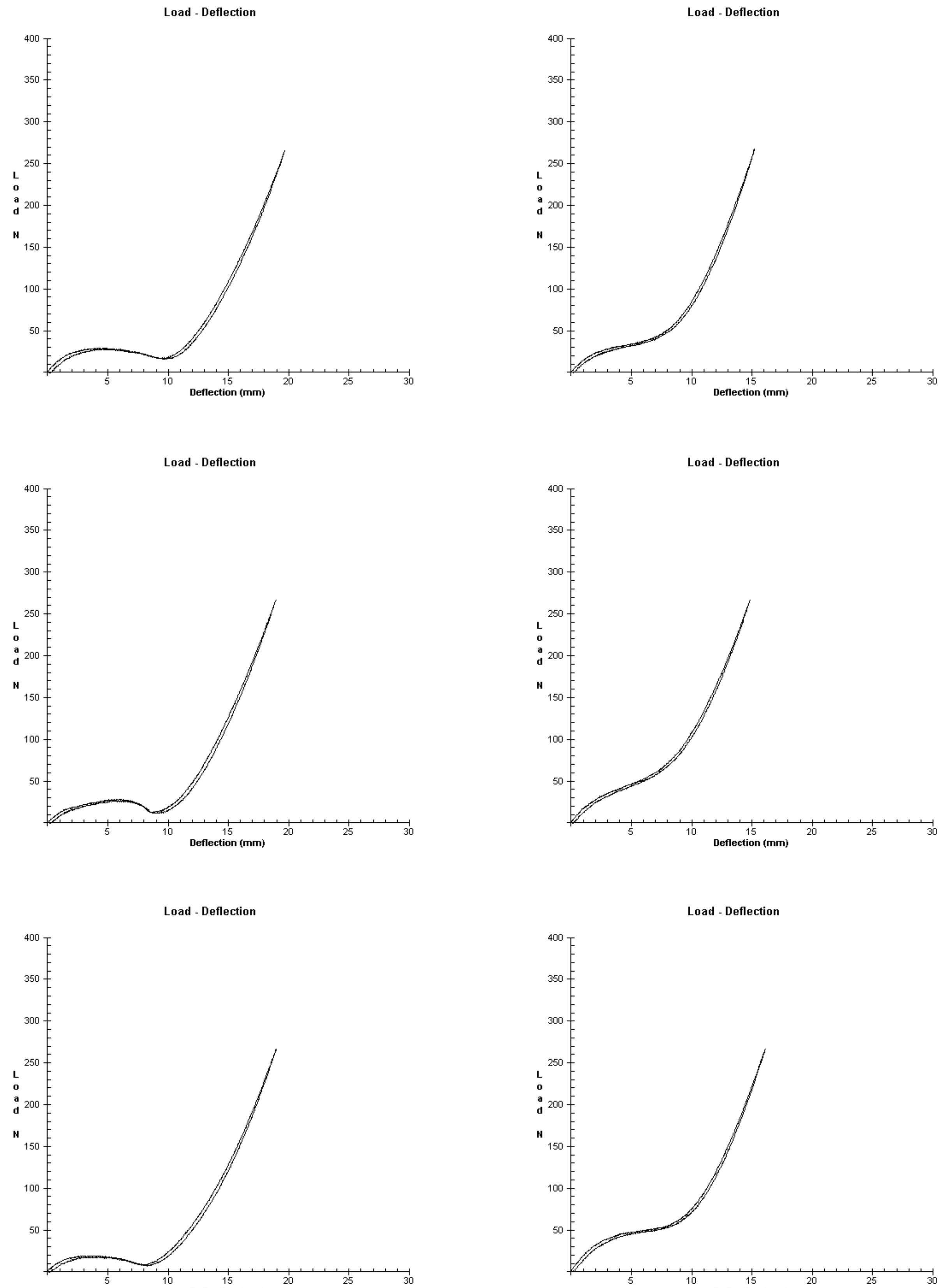

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Figure 2. Load – Deflection curves for hydroformed doors.

DP600 0.6 mm Location A Fixed Load Test   DP600 0.7 mm Location A Fixed Load Test

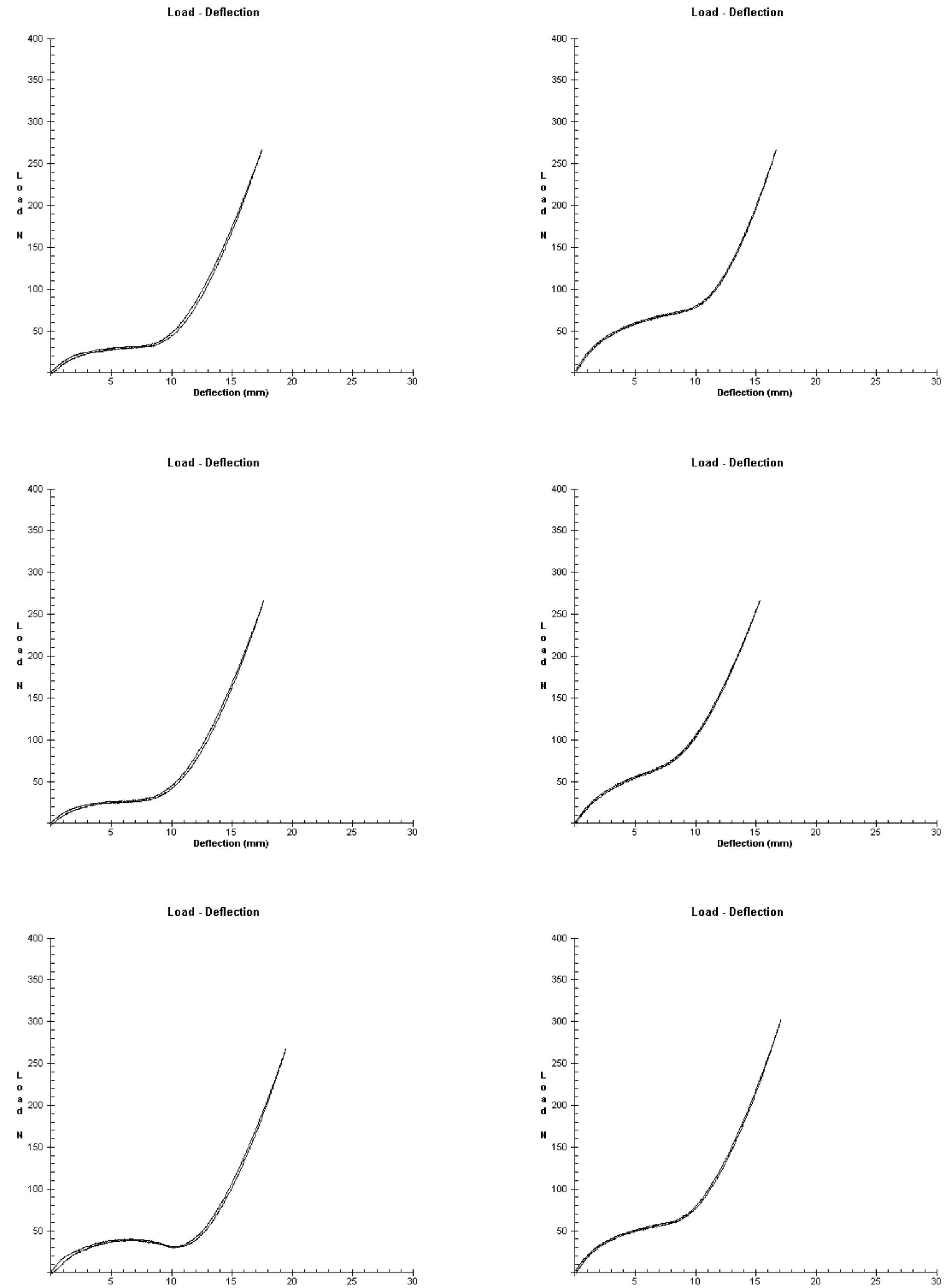

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Figure 3. Load – Deflection curves for stamped doors.

210BH 0.6 mm Location A Fixed Load Test | 210BH 0.7 mm Location A Fixed Load Test

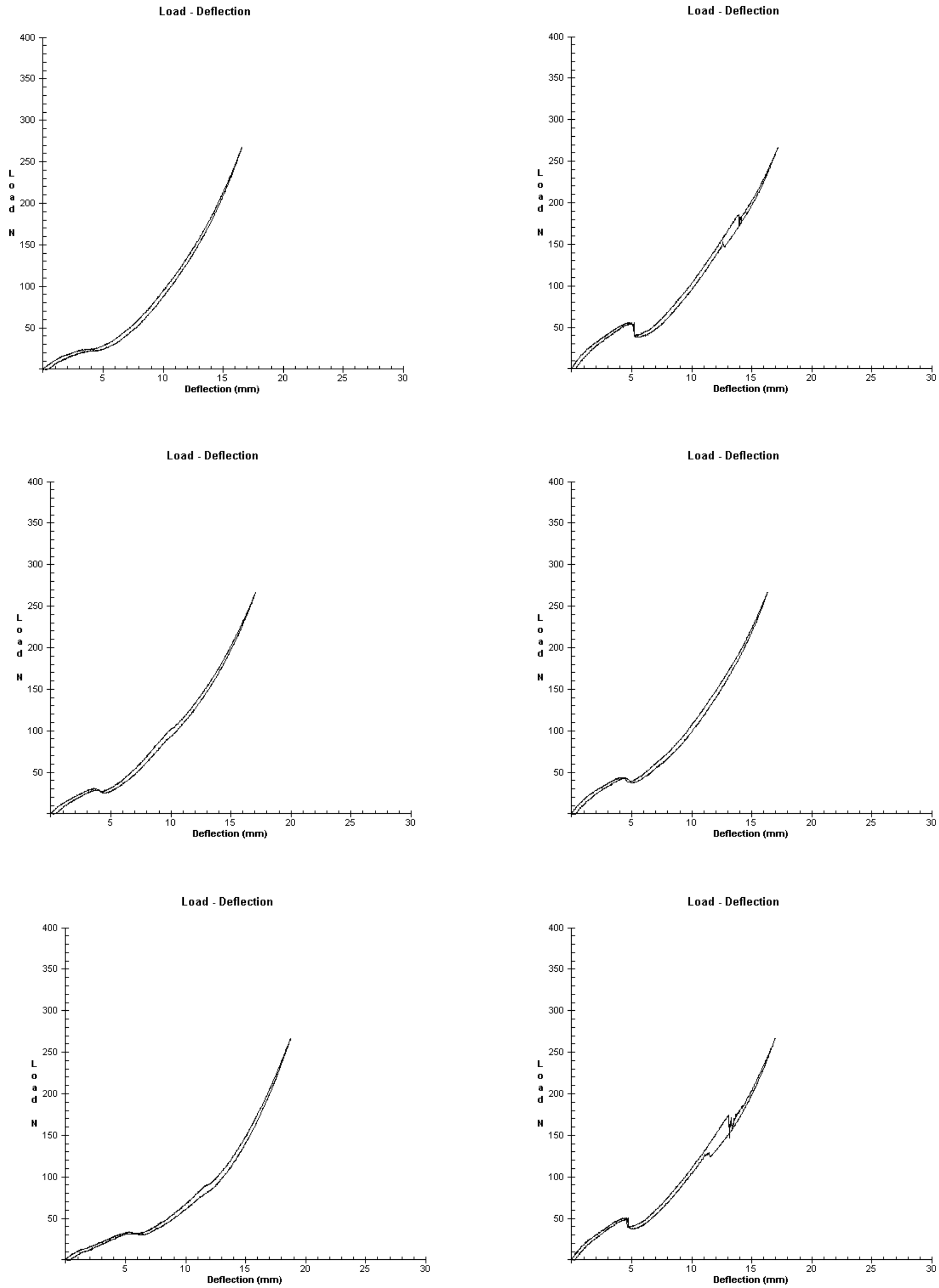

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Figure 3. Load – Deflection curves for stamped doors.

260BH 0.6 mm Location A Fixed Load Test 260BH 0.7 mm Location A Fixed Load Test

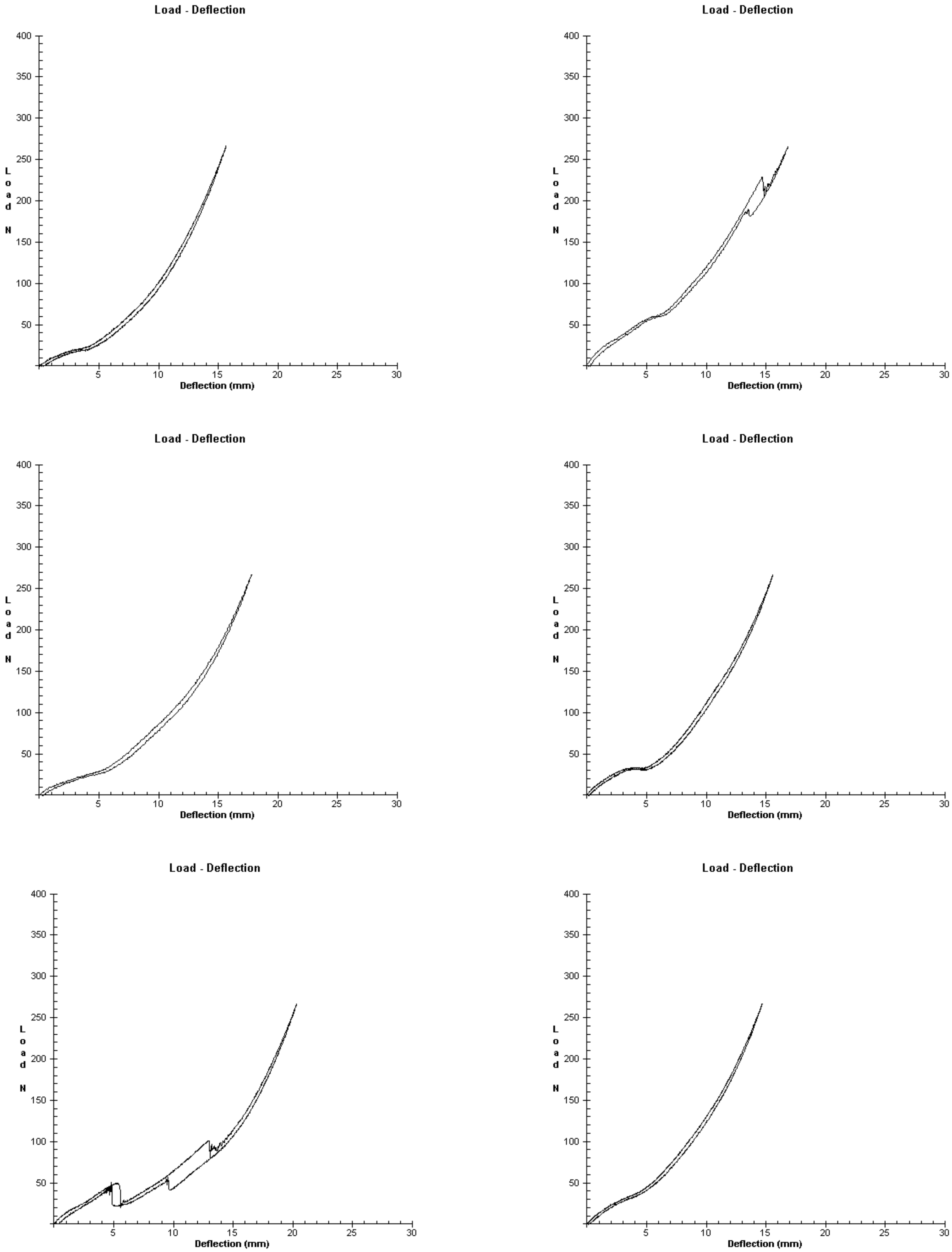

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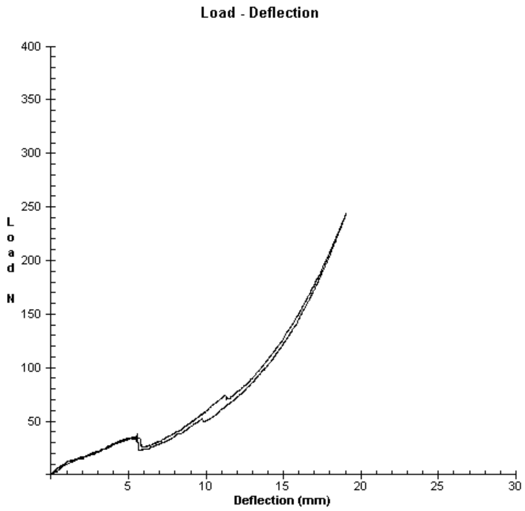
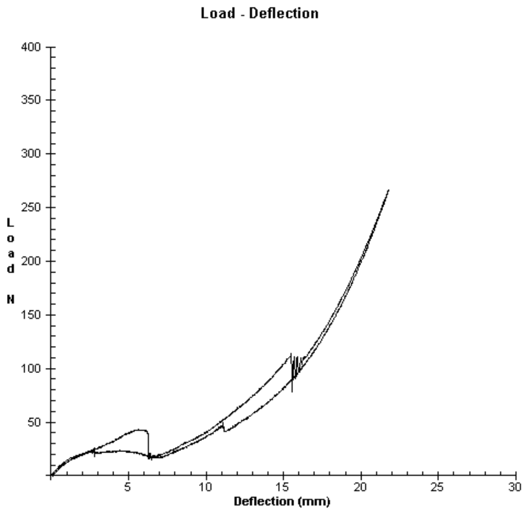
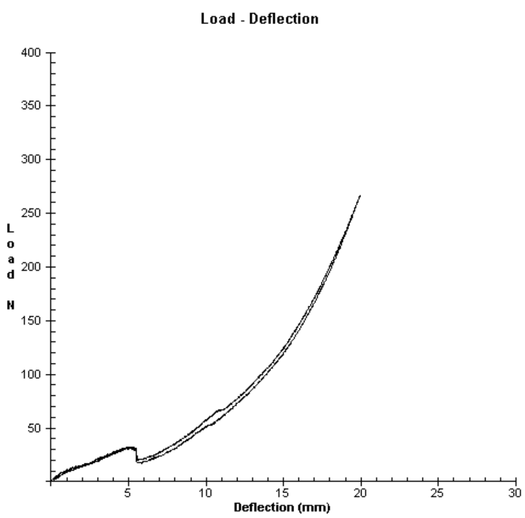
Figure 3. Load – Deflection curves for stamped doors.

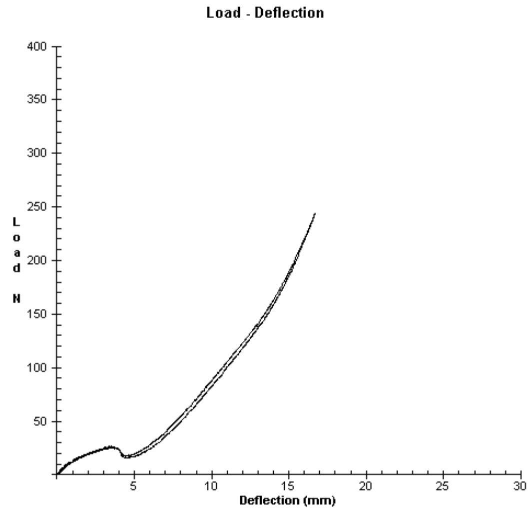
DP600 0.6 mm Location A Fixed Load Test

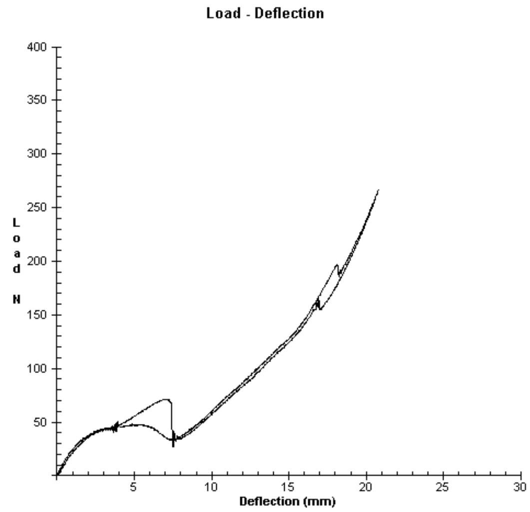






DP600 0.7 mm Location A Fixed Load Test





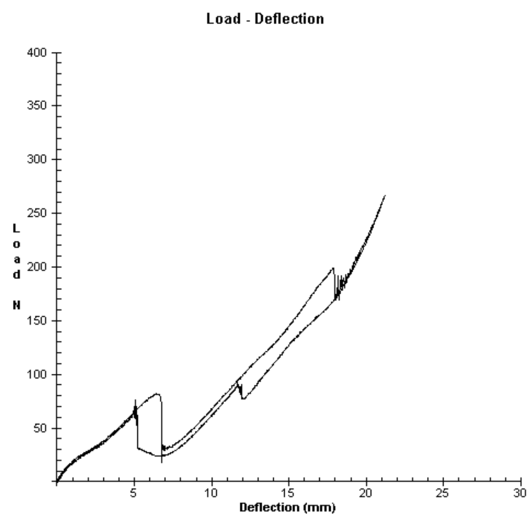


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Figure 3. Load – Deflection curves for stamped doors.

Quasi-Static Dent Resistance

The quasi-static incremental dent tests reveal dent resistance for the hydroformed doors that is quite similar to the dent resistance in the stamped doors (figure 4). Location C in the stamped doors has unusually high dent resistance because of the oil-canning which accompanied the dent testing. In the stiffer, upper region of the door, represented by location F, there is little difference between the stamped and hydroformed doors. It was anticipated that the hydroformed doors would exhibit more reproducible dent resistance, but the ranges of testing shown in figure 4 do not indicate such an improvement.

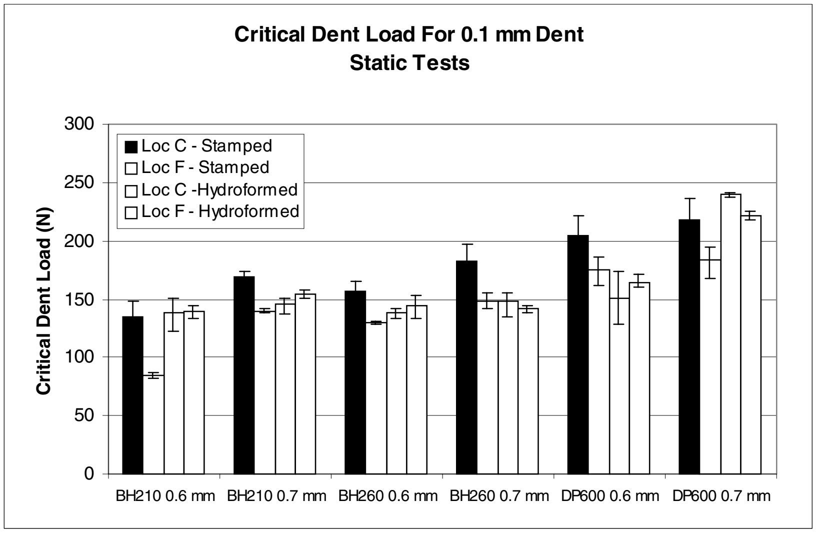

Figure 4. Quasi-static dent resistance results for a 0.1mm dent for locations C and F, with the range of values indicated.

Dynamic Dent Resistance

The dynamic dent resistance results are presented in Figure 5. They show the same relative behavior as the quasi-static results, but with improved dent resistance because of the positive strain rate sensitivity of steel.

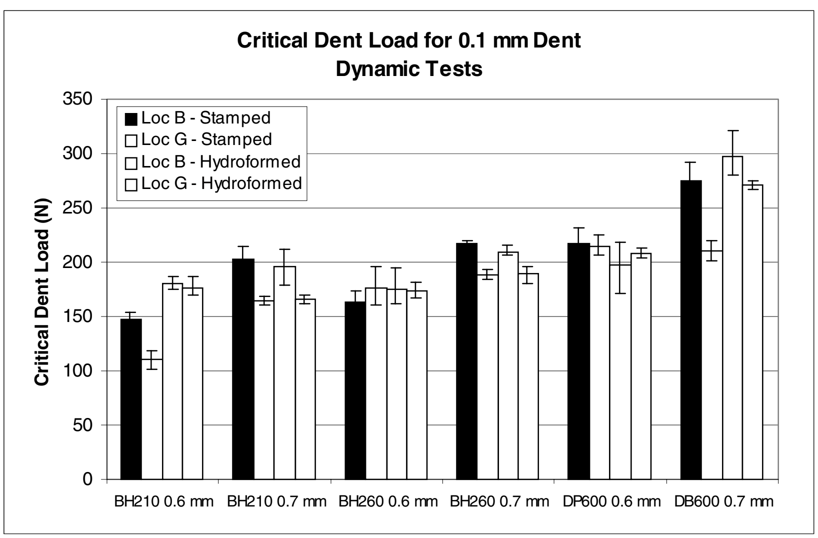

Figure 5. Critical dent load for a 0.1mm dent under dynamic conditions for locations B and G.

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Conclusions

1. The hydroformed ULSAC doors exhibited approximately the same dent resistance as the stamped ULSAC doors.
2. The hydroformed ULSAC doors exhibited improved oil-canning performance compared with the stamped ULSAC doors.
3. The dynamic dent resistance of the hydroformed ULSAC doors was approximately the same as the static ULSAC doors.

Acknowledgement

Special acknowledgement must be given to (name) who performed the dent testing in support of this project.

References

1. (Company name), “Dynamic dent testing of hydroformed ULSAC doors at (company name),” October 5, 2000.
2. Auto/Steel Partnership, “Procedures for Evaluating Dent Resistance of Steel Automotive Panels, Version 1.0 – June 1999.”
3. (Company name), “Results of Dent Testing of Stamped ULSAC Doors (WO3982),” March 4, 2000.

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Lab 2 – Material Properties – 27Oct2000

One each of the six hydroformed ULSAC door outer strength / gauge combinations was sectioned in the body (between Lab 2 dent test locations D and C) of the outer panel for tensile testing. ASTM tensile specimens were cut and prepared in the "L" (along length of door), "T" (top to bottom of door), and "D" (diagonal) directions.

Table I. Mechanical Property Results (shaded = stamped; unshaded = hydroformed)

Material	Sample	Thickness Bare (mm)	Yield Strength (MPa)	Yield Point Elongation (MPa)	Tensile Strength (MPa)	Uniform Elongation (%)	Total Elongation (%)	n Value	K Value (MPa)	Strain Range for n, K (%)
BH210-0.6	L	0.586	318	None	424	16.7	29.8	0.167	670	10.0-16.7
		0.574	371	2.7	419	7.5	22.5	0.109	599	2.9-7.4
BH210-0.6	D	0.587	317	None	401	18.1	31.9	0.164	635	10.0-18.1
		0.577	386	4.0	427	7.0	21.4	0.104	605	4.1-6.9
BH210-0.6	T	0.587	338	None	428	15.9	30.2	0.160	668	10.0-15.9
		0.576	371	2.6	416	7.3	22.9	0.107	593	2.8-7.2
BH210-0.7	L	0.684	284	0.9	375	18.1	33.6	0.166	591	10.0-18.1
		0.668	323	0.5	377	6.5	25.2	0.084	500	0.6-6.3
BH210-0.7	D	0.684	303	4.1	383	20.0	32.2	0.156	593	10.0-20.0
		0.671	339	Trace	395	6.1	22.3	0.095	548	2.1-6.0
BH210-0.7	T	0.682	303	3.9	370	17.0	33.0	0.156	578	10.0-17.0
		0.669	326	Trace	379	6.1	25.0	0.093	526	2.2-5.9
BH260-0.6	L	0.587	340	2.0	416	13.6	24.7	0.121	607	10.0-13.6
		0.560	383	0.5	452	6.4	16.5	0.085	603	0.6-6.3
BH260-0.6	D	0.595	336	3.2	408	13.9	26.1	0.134	612	10.0-13.9
		0.561	400	None	461	6.6	15.8	0.086	624	2.1-6.5
BH260-0.6	T	0.586	338	3.5	410	12.5	24.8	0.126	605	10.0-12.5
		0.563	394	0.6	456	5.7	18.2	0.084	607	0.7-5.5
BH260-0.7	L	0.684	311	2.5	403	15.5	30.0	0.151	624	10.0-15.5
		0.665	332	0.8	424	9.0	24.4	0.134	645	0.9-8.9
BH260-0.7	D	0.691	305	3.1	402	14.7	29.3	0.156	624	10.0-14.7
		0.667	339	0.7	426	8.5	23.0	0.124	630	0.8-8.4
BH260-0.7	T	0.689	306	2.5	399	17.7	31.7	0.156	623	10.0-17.7
		0.671	340	1.1	425	8.8	24.3	0.133	646	1.2-8.7
DP600-0.6	L	0.583	482	None	653	12.1	20.8	0.125	964	10.0-12.1
		0.588	428	None	647	12.5	21.6	0.136	976	10.1-12.5
DP600-0.6	D	0.578	482	None	662	13.2	22.1	0.123	971	10.0-13.2
		0.585	421	None	641	13.7	23.9	0.146	984	10.0-13.7
DP600-0.6	T	0.580	489	None	673	11.9	20.2	0.115	971	7.0-11.9
		0.585	421	None	641	13.7	23.9	0.146	984	10.0-13.7
DP600-0.7	L	0.680	474	None	632	13.7	22.4	0.140	961	10.0-13.7
		0.671	509	None	647	11.2	20.7	0.110	924	7.0-11.2
DP600-0.7	D	0.673	480	None	643	14.7	23.2	0.137	971	10.0-14.7
		0.667	511	None	646	12.8	23.4	0.108	916	10.1-12.8
DP600-0.7	T	0.675	487	None	652	14.1	22.0	0.130	970	10.1-14.1
		0.672	526	None	657	10.5	22.3	0.113	944	7.0-10.5

Note: Samples tested with coating. Coating only removed to establish thickness for cross-sectional area.

Lab 2 – Report – 14Dec2000

Dent Test Results for Three Hydroformed Electrogalvanized Dual Phase 600 Doors for the ULSAC Program (WO 4395)

Summary

Three ULSAC doors with sheet-hydroformed outer panels were dent tested at the (company name). The doors had electrogalvanized dual phase 600 0.6mm outer skins. The denting behaviors of these doors were compared with identical doors whose outers consisted of sheet-hydroformed hot dip galvanized dual phase 0.6mm and 0.7 mm steel. Quasi-static dent resistance, dynamic dent resistance, and the quasi-static load - deflection curve were determined for each door at specified locations.

The electrogalvanized DP600 0.6mm doors exhibited slightly better dent resistance than the GI DP600 0.6mm doors except in the area of oil-canning. The electrogalvanized DP600 doors exhibited more severe hard oil-canning behavior.

Three assembled steel doors with sheet-hydroformed outer panels, provided by the Ultra-Light Steel Auto Closures (ULSAC) program, were dent tested at the Lab 2 Application Center. The door outers were made from electrogalvanized dual phase 600 steel 0.06mm in thickness.

Dent testing was performed on the Lab 2 dent tester using the Auto/Steel Partnership (A/SP) draft procedure (1). This procedure consists of a quasi-static incremental dent test, which yields a dent load – dent depth relationship. A quasi-static fixed load test and dynamic (250mm/s) incremental tests were also performed on each door.

Results were compared with testing of identical doors with sheet-hydroformed outers made from hot dip galvanized DP600 0.6mm and 0.7 mm steel previously reported (2).

Procedure

The procedure used was described in the report of the previous testing (3). A critical dent depth of 0.1mm was used for the quasi-static and dynamic testing. The locations tested are presented in Figure 1.

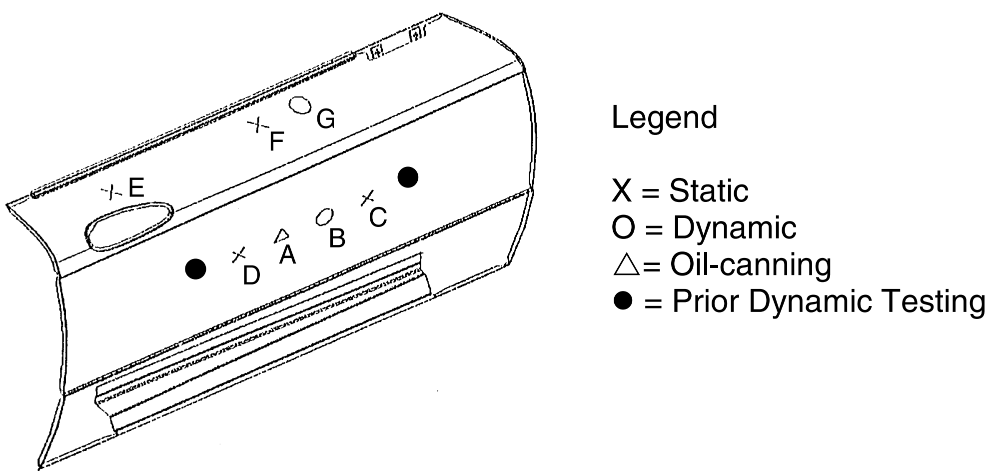

Figure 1. Test locations.

Results

Panel Weights

The mass of one of the hydroformed EG dual phase 600 0.6mm doors and previously tested hydroformed GI DP600 0.6mm and 0.7mm doors were measured. The results were:

EG DP600 0.6mm	9.68kg
GI DP600 0.6mm	9.80kg
GI DP600 0.7mm	10.32kg

Quasi-Static Incremental Testing

The results of the quasi-static incremental dent tests are given in table 1.

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Table I. Quasi-Static Incremental Dent Test Results								
	Location C		Location D		Location E		Location F	
Panel	Stiffness (N/mm)	Critical Dent Load at 0.1 mm Dent Depth (N)	Stiffness (N/mm)	Critical Dent Load at 0.1 mm Dent Depth (N)	Stiffness (N/mm)	Critical Dent Load at 0.1 mm Dent Depth (N)	Stiffness (N/mm)	Critical Dent Load at 0.1 mm Dent Depth (N)
EG DP600-0.6*	15	193	20	172	36	196	22	159
GI DP600-0.6*	11	150	11	145	25	144	33	164
GI DB600-0.7	18	240	21	220	41	220	29	222

* indicates hard oil-canning

Quasi-Static Single Load Testing
Hard oil-canning, marked by a drop in load on the load – deflection curve from single increment, fixed load testing, occurred in the locations marked. All panels displayed "soft" oil-canning, which is the presence of an inflection point in the load – deflection curve. Those panels displaying some hard oil-canning are indicated with an asterisk in the panel column of table I.

Dynamic Incremental Dent Testing
The dynamic incremental test results are given in table II.

Table II. Dynamic Incremental Dent Test Results		
	Critical Dent Load at 0.1 mm Dent Depth (N)	
Panel	Location B	Location G
EG DP600-0.6	277	181
GI DP600 - 0.6	198	208
GI DB600 - 0.7	297	271

Discussion

Oil-canning
The oil-canning behavior of the EG DP600 0.6 mm doors were more severe than both the 0.6mm and 0.7mm hydroformed GI DP600 doors tested previously. The load - deflection curves for the fixed load tests on the hydroformed EG DP600 doors tested in this study are given in figure 2; the curves from the previously tested hydroformed GI DP 600 doors are given in figure 3.

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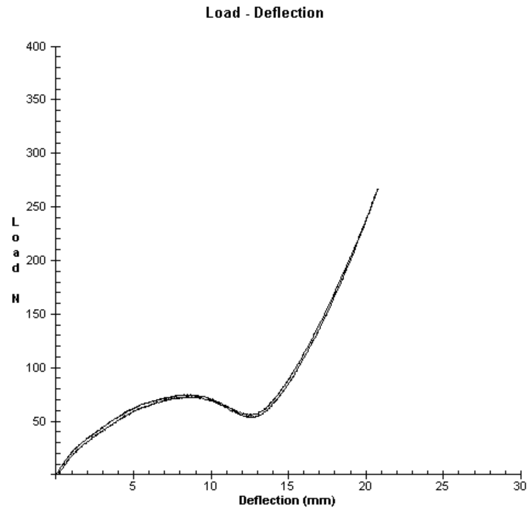
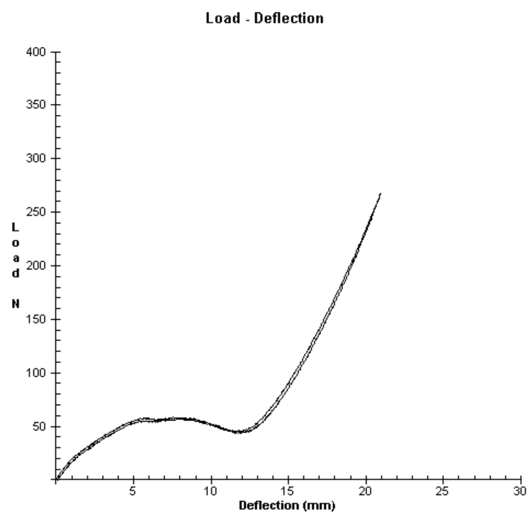
Figure 2. Load – deflection curves for EG DP600 0.6mm hydroformed doors.





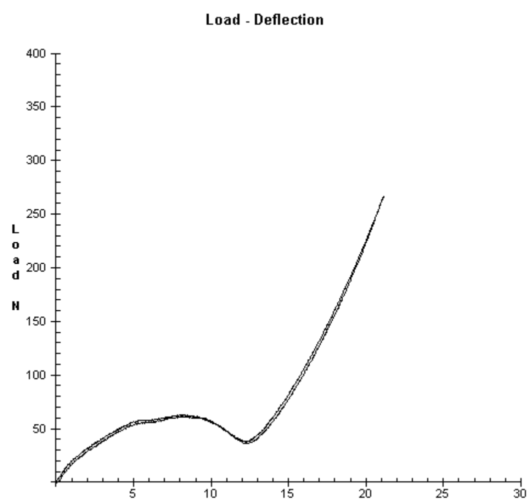


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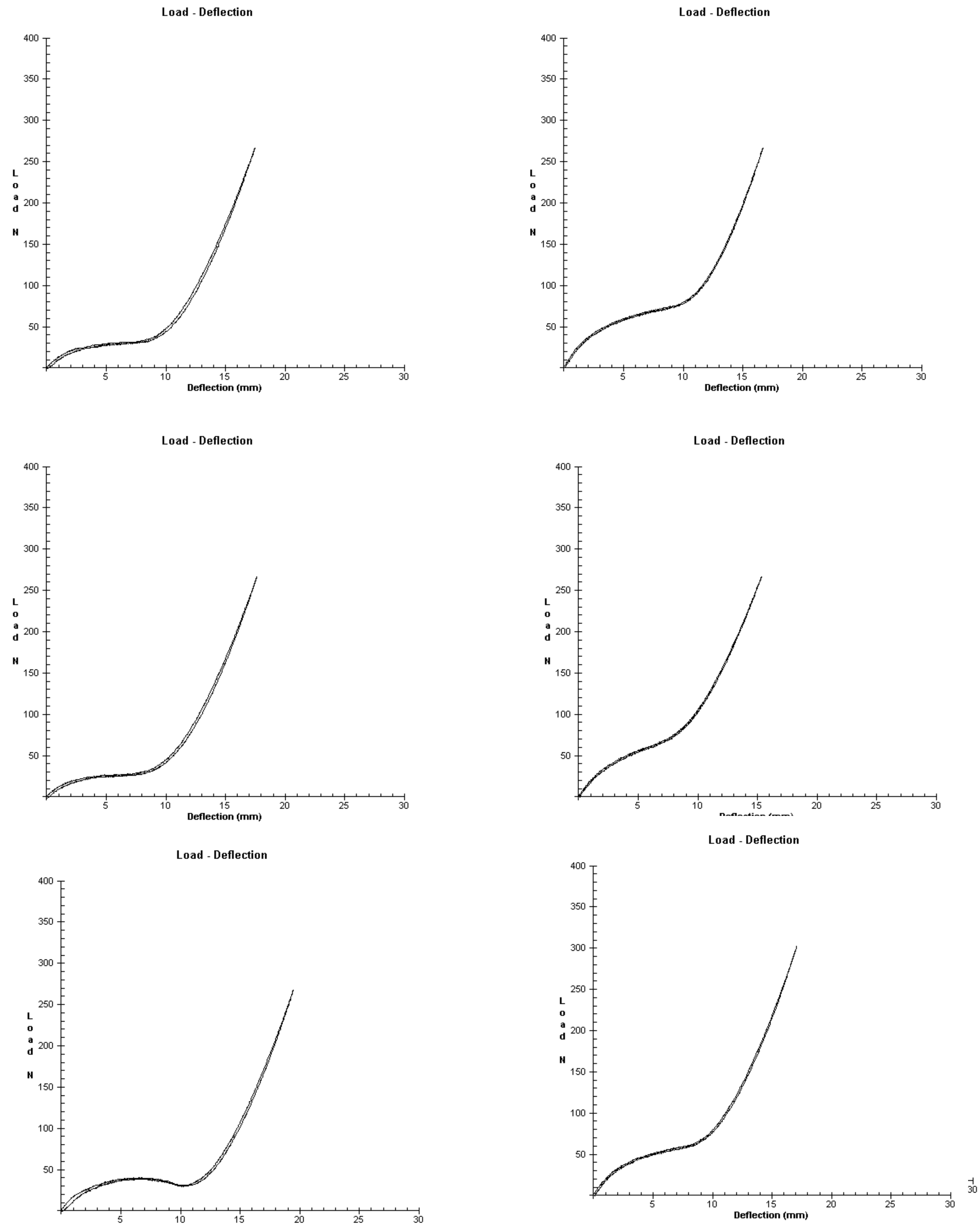
Figure 3. Load – deflection curves for GI DP600 0.6mm and 0.7mm hydroformed doors.

GI DP600 0.6mm Location A Fixed Load Test GI DP600 0.7mm Location A Fixed Load Test



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Quasi-Static Dent Resistance

The quasi-static incremental dent tests reveal dent resistance for the EG DP600 0.6mm doors that is quite similar to, but generally better than, the dent resistance in the GI DP600 0.6mm doors (figure 4).

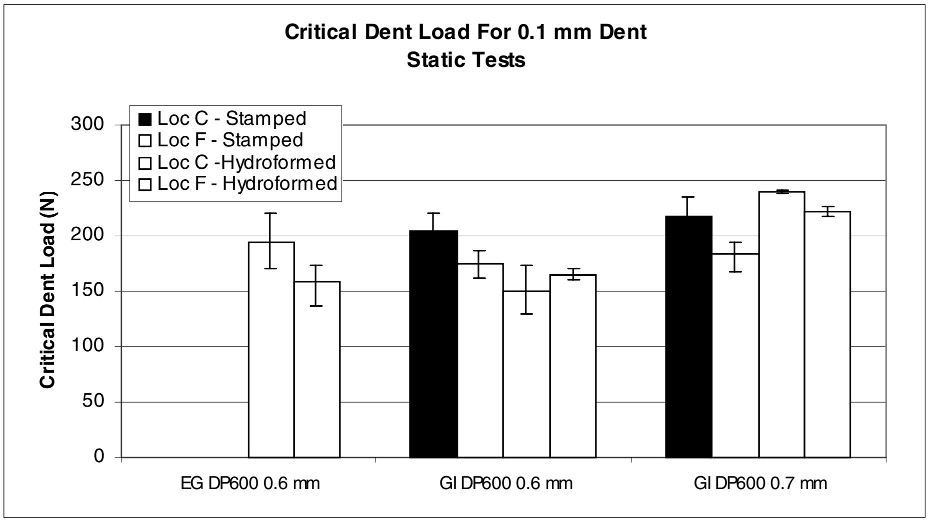

Figure 4. Quasi-static dent resistance results for a 0.1mm dent for locations C and F, with the range of values indicated.

Dynamic Dent Resistance

The dynamic dent resistance results are presented in Figure 5. The B location is unusually high in the EG DP600 doors, but the G location more closely follows the GI DP600 doors.

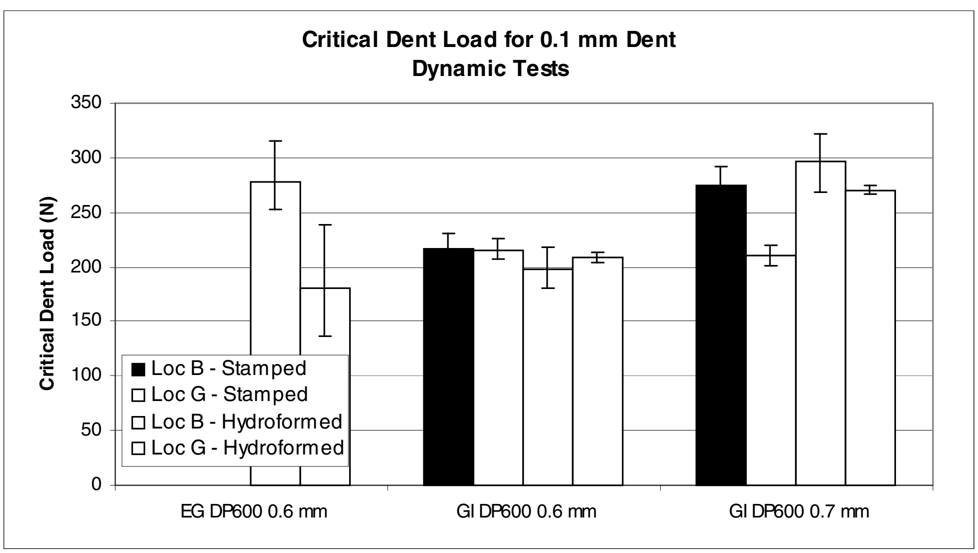

Figure 5. Critical dent load for a 0.1mm dent under dynamic conditions for locations B and G.

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Conclusions

The EG DP600 0.6 mm doors exhibited improved dent resistance than the GI DP600 0.6mm doors except in the occurrence of oil-canning, which was evident in all three EG doors but in only one of the GI DP600 0.6 mm doors.

Acknowledgement

Special acknowledgement must be given to (name) who performed the dent testing in support of this project.

References

1. Auto/Steel Partnership, "Procedures for Evaluating Dent Resistance of Steel Automotive Panels, Version 1.0 – June 1999."
2. (Company name), "Results of Dent Testing of Hydroformed ULSAC Doors (WO 4334)," October 27, 2000.
3. (Company name), "Results of Dent Testing of Stamped ULSAC Doors (WO3982)," March 4, 2000.

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Lab 2 – Material Properties – 14Dec2000

ULSAC DOOR (EG DP600) TENSILE RESULTS

One of the three 0.6mm EG DP600 hydroformed ULSAC door outers was sectioned in the body (between NSC dent test locations D and C) for tensile testing. ASTM tensile specimens were cut and prepared in the "L" (along length of door), "T" (top to bottom of door), and "D" (diagonal) directions. Results of tensile tests are presented in Table I below along with the previous HDG DP600 stamped and hydroformed panel results.

Table I. Mechanical Property Results (shaded = stamped; unshaded = hydroformed)

Material	Sample	Thickness Bare (mm)	Yield Strength (MPa)	Yield Point Elongation (MPa)	Tensile Strength (MPa)	Uniform Elongation (%)	Total Elongation (%)	n Value	K Value (MPa)	Strain Range for n, K (%)
HDG DP600-0.6	L	0.583	482	None	653	12.1	20.8	0.125	964	10.0-12.1
		0.588	428	None	647	12.5	21.6	0.136	976	10.1-12.5
HDG DP600-0.6	D	0.578	482	None	662	13.2	22.1	0.123	971	10.0-13.2
		0.585	421	None	641	13.7	23.9	0.146	984	10.0-13.7
HDG DP600-0.6	T	0.580	489	None	673	11.9	20.2	0.115	971	7.0-11.9
		0.585	421	None	641	13.7	23.9	0.146	984	10.0-13.7
EG DP600-0.6	L	0.563	617	None	702	3.3	14.3	0.030	805	2.1-3.1
	D	0.563	673	None	694	5.4	17.5	0.041	825	2.0-5.3
	T	0.561	674	None	711	4.6	13.3	0.051	872	1.1-4.2

Note: Samples tested with coating. Coating only removed to establish thickness for cross-sectional area.

Compared to the 0.6mm HDG DP600 hydroformed door outer material, the EG DP600 exhibited significantly higher yield strength, higher tensile strength, lower elongation, and lower thickness in the as-formed condition.

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4. Structural Performance Report

Porsche Engineering Services, Inc.

Testing for Structural Performance
ULSAC Door Structure with Sheet Hydroformed Panel Front Door Outer
with DP600 0.6mm thickness

Table of Contents

Page

Porsche Engineering Services, Inc.

Testing for Structural Performance
ULSAC Door Structure with Sheet Hydroformed Panel Front Door Outer
with 0.6mm thickness

1.0 OBJECTIVE

The purpose of this test was to evaluate the structural performance of the ULSAC DH door structure with the Panel Front Door Outer Material in 0.6mm thickness.

2.0 PROCEDURE

The door structure was tested under the same conditions as described in the ULSAC Engineering Report – April 2000, Chapter 10 Testing and Results for the door structure with a 0.7mm thickness Panel Front Door Outer.

3.0 RESULTS

3.1 Upper Lateral Stiffness Test

Latch bolt to top load point measurement along Z-axis: 270 mm
Top measurement point to lower measurement point along Z-axis:455 mm

Table No. 1: Upper Lateral Stiffness Test Results

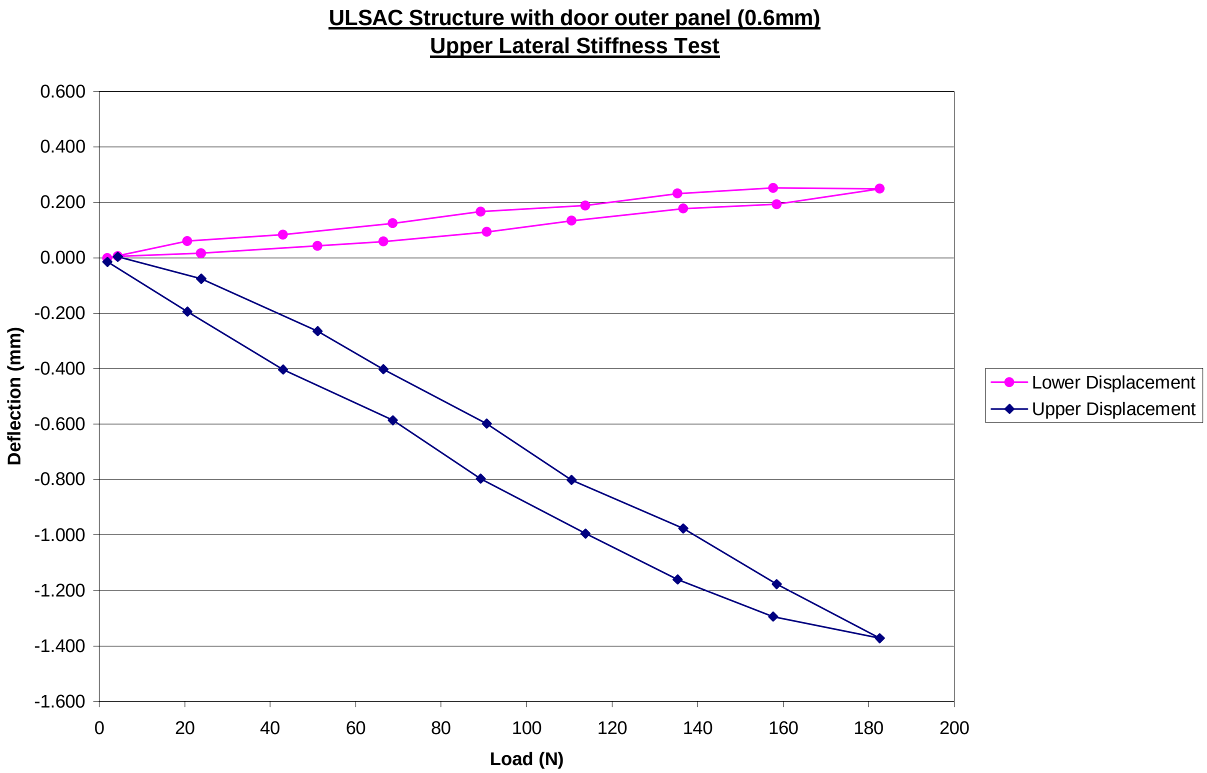
Outboard Load	**183 N**	
Indicator Location	Top Load Point	Bottom Load Point
Deflection	1.371 mm out	0.248 mm in
Set	0.014 mm out	0.000 mm
Stiffness	242 N-m/deg	---

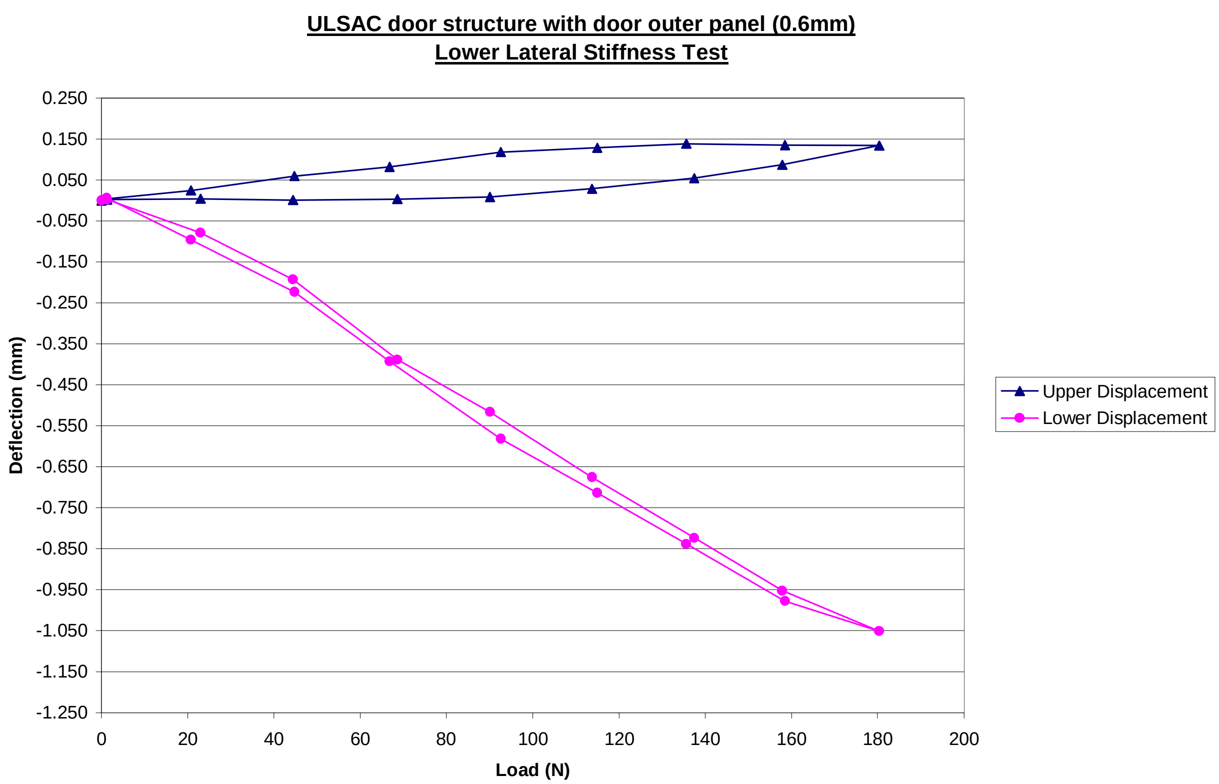
3.2 Lower Lateral Stiffness Test Results

Latch bolt to bottom load point measurement along Z-axis: 172 mm
Lower measurement point to top measurement point along Z-axis:445 mm

Table No. 2: Lower Lateral Stiffness Test Results

Inboard Load	**180 N**	
Indicator Location	Top Load Point	Bottom Load Point
Deflection	0.134 mm out	1.051 mm in
Set	0.000 mm	0.000 mm
Stiffness	---	203 N-m/deg

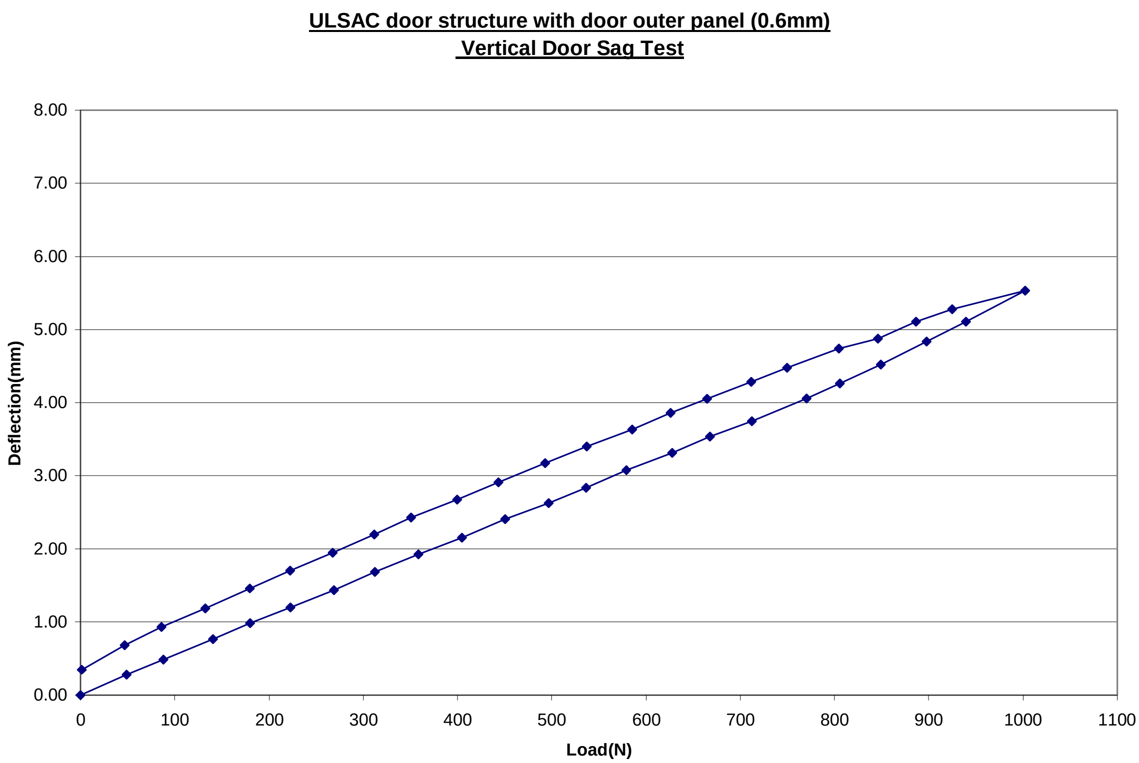

ULSAC Structure with door outer panel (0.6mm)
Upper Lateral Stiffness Test
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.600
-0.800
-1.000
-1.200
-1.400
-1.600
Deflection (mm)
0
20
40
60
80
100
120
140
160
180
200
Load (N)
Lower Displacement
Upper Displacement


ULSAC door structure with door outer panel (0.6mm)
Lower Lateral Stiffness Test
0.250
0.150
0.050
-0.050
-0.150
-0.250
-0.350
-0.450
-0.550
-0.650
-0.750
-0.850
-0.950
-1.050
-1.150
-1.250
Deflection (mm)
0
20
40
60
80
100
120
140
160
180
200
Load (N)
Upper Displacement
Lower Displacement

3.3 Vertical Door Sag Test

<u>Table No. 3:</u> Vertical Door Sag Test Results

Downward Load	**1002 N**
Indicator Location	Latch Vertical
Deflection	5.531 mm down
Set	0.346 mm down
Stiffness	181 N/mm



5. Economic Analysis

Cost Model ULSAC - Sheet Hydroforming

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